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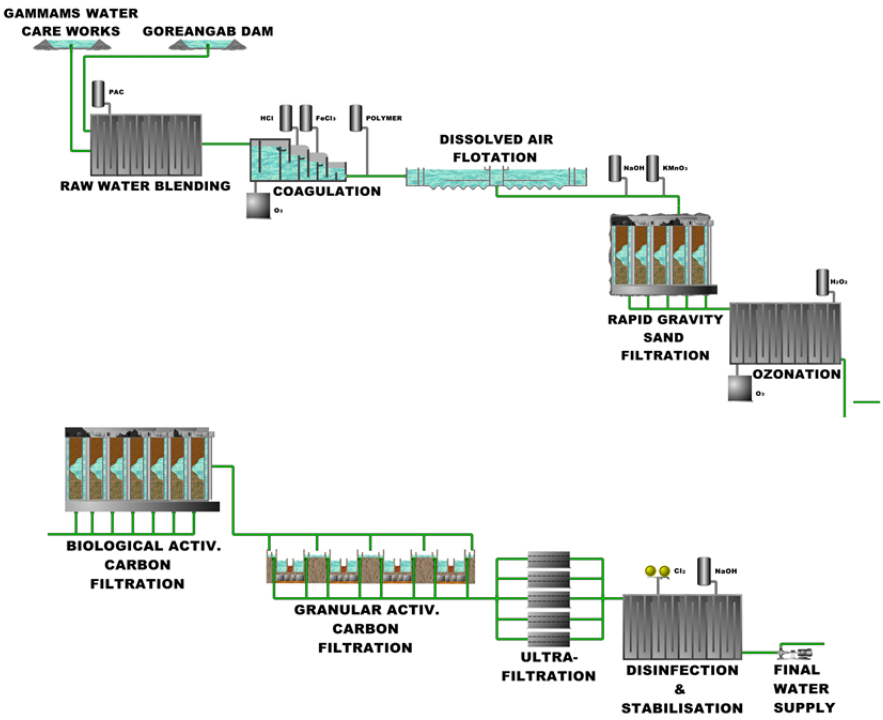

Microbiological Risk Assessment of the Water Reclamation Plant in Windhoek, Namibia

Master of Science Thesis in the Master's Programme Geo and Water Engineering

HELEN ANDER, MADELEINE FORSS

Department of Civil and Environmental Engineering
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ABSTRACT

The overall aim with this Master's Thesis was to perform a microbiological risk assessment of the New Goreangab Water Reclamation Plant (NGWRP) in Windhoek, Namibia. The emphasis was on the consumers' health regarding the microbiological quality of the drinking water.

NGWRP is a water treatment plan producing drinking water from treated sewage. The study was performed with a Fault tree analysis (FTA) that provided a risk estimation of the treatment processes at NGWRP. Moreover, a Quantitative microbial risk assessment (QMRA) was performed to model the NGWRP with different scenarios. Hence, the annual risk of infection by the pathogens *Norovirus*, *Giardia* and *Cryptosporidium* were obtained, for the drinking water consumers. The result was compared with a health based target of 10^{-4} annual probability of infection.

In the FTA result, the mean value of the total microbiological risk at NGWRP was 134 failure hours/year, where 55 failure hours were caused by power supply. Furthermore, the treatment processes conventional treatment, ozonation, ultra membrane filtration and chlorination caused 37, 19, 25 and 18 failure hours per year respectively. The QMRA result showed that the risk of infection by *Norovirus* and *Giardia* is very low. The probabilities of infection by *Cryptosporidium* were acceptable for the modelled scenarios, but the 95^{th}-percentiles were near the target level and even too high when the raw water levels were increased.

In order to decrease the risk levels, it was proposed to further investigate the possibilities of a local power supply at NGWRP. Furthermore, it was suggested to introduce UV light as an additional treatment to decrease the risk of infection by *Cryptosporidium*.

Key words: Risk assessment, Fault tree analysis, Quantitative microbial risk Assessment, Reclaimed water, Water scarcity, Windhoek, Namibia

Mikrobiologisk riskanalys av New Goreangab Water Reclamation Plant i Windhoek, Namibia

Examensarbete inom masterprogrammet Geo and Water Engineering

HELEN ANDER, MADELEINE FORSS

Institutionen för bygg- och miljöteknik

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SAMMANFATTNING

Syftet med detta examensarbete var att utföra en mikrobiologisk riskanalys för New Goreangab Water Reclamation Plant (NGWRP) i Windhoek, Namibia. Studien var inriktad på hälsorisker för dricksvattenkonsumenterna gällande den mikrobiologiska kvaliteten.

NGWRP är ett vattenreningsverk som producerar dricksvatten från renat avloppsvatten. Undersökningen bestod av en felträdsanalys (FTA) där riskerna uppskattades för de olika reningsprocesserna på NGWRP. Det utfördes även en mikrobiologisk riskanalys (MRA) för att modellera reningsverket med olika scenarier. Således kunde infektionsrisken för patogenerna *Norovirus*, *Giardia* och *Cryptosporidium* utredas för dricksvattenkonsumenterna. Värdena jämfördes med ett riktvärde motsvarande en årlig infektionssannolikhet på 10^{-4}.

Enligt FTA:n så var medelvärdet för den totala mikrobiologiska risken för NGWRP 134 feltimmar per år, varav 55 feltimmar orsakades av elförsörjningen. För reningsprocesserna konventionell rening, ozonering, ultra membranfiltrering och klorering så var det 37, 19, 25 och 18 feltimmar per år. Resultaten från den mikrobiologiska riskundersökningen visade på tillräckligt låg infektionsrisker för *Norovirus* och *Giardia*. Infektionsriskerna för *Cryptosporidium* var acceptabla för de modellerade scenariorna, men 95^{e}-percentilerna var nära riktvärdet och till och med för hög när vid ökade patogenhalter i råvattnet.

I syfte att minska riskerna så föreslogs det att utreda möjligheterna till en lokal elförsörjning för NGWRP. Dessutom föreslogs UV-ljus som ett ytterligare reningssteg på NGWRP för att minska infektionsrisken för *Cryptosporidium*.

Nyckelord: Risk undersökning, Felträdsanalys, Mikrobiologisk riskundersökning, vattenåtervinning, vattenbrist, Windhoek, Namibia

Contents

Preface

We would like to express gratitude to all those who made it possible for us to complete this Master thesis' at Chalmers University of Technology in Gothenburg. We want to thank our supervisor assistant Prof. Thomas Pettersson at the division Water Environment Technology at the department Civil and Environmental Engineering for assistance in the work and initiation of the study. We also want to thank Dr. Andreas Lindhe at the GeoEngineering division for the valuable help with carrying out the Fault tree analysis and adjunct Prof. Olof Bergstedt for great assistance when performing the Quantitative microbial risk assessment.

Furthermore, we want thank Dr. Johan Åstrand , Dr. Britt-Marie Wilén and doctoral student Ekaterina Sokolova at the division Water Environment Technology for the help with the work at Mölndal drinking water plant. Furthermore, we want thank our examiner Prof. Greg Morisson and Prof. Per-Arne Malmquist for inspiration. We also want to thank the operation technicians Reine Rohman and Dennis Yhr at Mölndal drinking water plant for good knowledge and help.

We want to thank and express gratitude to Mr Jürgen Menge at City of Windhoek for the initiative of the study and the supervision of the work. Furthermore we are thankful for the hospitability he and his family showed us. Furthermore we want to thank Mr John Esterhuizen, Mr Siegfried Mueller, Mr René Mertens and Mr James Villet at WINGOC and consultant Mrs Truddy Theron-Beukes in Windhoek, Namibia for helping us with the workshop and for giving us a better understanding of the processes as NGWRP. Moreover, they thought us about the beautiful Namibia and served well prepared coffee and made our study more pleasant. We also want to thank all the staff at WINGOC and the laboratory staff of Gammams Water Care Work, for assisting us and making us feel very welcome.

We want to thank Yvonne Young for practical help with the MFS applications. For the financial support in form of a scholarship, we are grateful to SIDA for the possibility to perform a Minor Field Study (MFS) in Windhoek, Namibia.

Gothenburg August 2011

Helen Ander & Madeleine Forss

Abbreviations

ALARP	As low as reasonably practice
AWWA	American Water Works Association
BAC	Bacteriological activated carbon
BrO_3^-	Bromide
CML	Customer Minutes Lost
Cl_2	Chlorine
Ct-value	Disinfectant concentration * Contact time
DAF	Dissolved air flotation
DOC	Dissolved organic removal
ER	Enhanced risk level
FTA	Fault tree analysis
$FeCl_3$	Ferric chloride
GAC	Granular activated carbon
GDP	Gross Domestic Product
GWCW	Gammams Water Care Work
HCl	Hydrochloric acid
HOCl	Hypochlorous acid
H_20_2	Hydrogen peroxide
LaRRI	Labour Resource and Research Institute
MAWF	Ministry of agriculture, water and forestry
MC	Monte Carlo
MTTF	Mean time to failure
MDT	Mean downtime
NR	Normal risk level
MnO_4	Permanganate
NaOCl	Sodium hypochlorite
NaOH	Sodium Hydroxide
NGWRP	New Goreangab Water Reclamation Plant
OCl^-	Hypochlorite
O_2	Oxygene
O_3	Ozone
OGWRP	Old Goreangab Water Reclamation Plant
PAC	Powder activated carbon
P	Probability
P_F	Probability of failure
P_I	Annual probability of failure
PLC	Programmable logic controller
PDF	Probability density function
PSA	Pressure swing absorb
QMRA	Quantitative microbial risk assessment
SCADA	Supervisory Control and Data Acquisition Centre
TECHNEAU	Technology Enabled Universal Access to Safe Water

THM:s	Trihalomethanes
UF	Ultra membrane filtration
UNDP	United Nations development programme
UV	Ultra violet
VOD	Vent ozone destructor
VSD	Variable speed drive
WASP	Water Supply and Sanitation Policy
WHO	World health organization
WINGOC	Windhoek Goreangab Operation Company
WSP	Water Safety Plan
WTP	Water treatment plant
WWTP	Wastewater treatment plant
ZMS	Zeoliten molecular sieve

Introduction

The water supplies in the world are shrinking (AWWA 2008) and already today around 1.1 billion people have physical water scarcity. Water scarcity is the imbalance between access and demand of water, in other words degradation of groundwater and surface water quality (WHO 2008).

Sub-Sahara countries have the lowest coverage rate in the world with respect to water supplies (UNDP 2006). One of the countries in that region is Namibia, that has a dry and a semiarid climate where water resources are scarce (Flod & Landquist 2010). One alternative in such an area is to produce drinking water from treated wastewater, so called reclaimed water (AWWA 2008). Since the year 1968 the capital of Namibia, Windhoek, has used reclaimed wastewater as one of their drinking water sources (van der Merwe 2005), which nowadays represent about 14% of the city's drinking water production (Menge et al. 2006).

The reclaimed water is treated at the New Goreangab Water Reclamation Plant (NGWRP) with four main processes: conventional treatment, ozonation, ultra membrane filtration (UF) and chlorination. Treating reclaimed water for drinking water purposes always involves different kinds of risks and therefore risk evaluation and control is particularly important. Many research projects have been performed at NGWRP. One project was started within the TECHNEAU project and began in 2007 (www.techneau.org). It was a risk assessment of NGWRP, this Master's Thesis continues what was started in 2007 but is not a part of the TECHNEAU.

This Master's Thesis evaluated the microbiological risks at NGWRP. Moreover, this risk assessment was performed with a Fault tree analysis (FTA) and a Quantitative microbiological risk assessment (QMRA). With the same methods, a pre-study was performed by the authors at Mölndal Drinking water treatment plant in Sweden.

1.1 Aims and Objectives

The aim of this Master's Thesis was to perform a microbiological risk assessment of the New Goreangab Water Reclamation Plant (NGWRP). The emphasis was on the consumers' health regarding the microbiological quality of the drinking water where the pathogens *Norovirus*, *Giardia* and *Cryptospordium* were considered.

The following questions were answered by performing a dynamic Fault tree analysis (FTA) and a Quantitative microbial risk assessment (QMRA) at NGWRP:

- What are the risks and the vulnerabilities of the different treatment steps at NGWRP?

- What is the probability for the inhabitants in Windhoek to be infected by pathogens ingested through drinking water, originating from the NGWRP?

Furthermore, the methods used were evaluated and possible countermeasures to decrease the risks for the consumers were discussed.

1.2 Delimitations

The risk assessment considered the water reclamation plant NGWRP and did not primarily include the water quality risks involved with the raw water sources and the distribution system. Moreover, generalizations and simplifications are always a part of risk analysis, as well as in this study.

2 Background

This chapter describes water reclamation in the world, gives a brief introduction to Namibia and some of the water issues in the country and the Namibian government's management strategies regarding drinking water safety. Finally, an overview of the pathogens *Giardia, Cryptosporidium* and *Norovirus* and indicator organisms that are used in this study are presented.

2.1 Water reclamation worldwide

Water reclamation is production of water from treated wastewater for different kind of purposes e.g. irrigation and drinking water. The importance of reclaimed water treatment has increased and has been introduced in many parts of the world (AWWA 2008). Reclaimed water can be applied for different purposes, more seldom for potable purposes. There are many examples in the world were reclamation of water is utilised (USEPA 2004). Moreover, in Israel there is a shortage of fresh water and the use of reclaimed water has been implemented and resulted in a treatment of 70% of the municipal wastewater, which is used for irrigation. Another example is Mexico where reclaimed water is utilised for both agriculture and urban purposes. Singapore is a country with a growing population and has since 2003 utilised reclaimed water for industries and other non potable uses as e.g. cooling water unit in ventilation systems.

Reclaimed water is sometimes considered a more reliable water resource compared to others, as the quantity of the produced water is predictable throughout rainy and dry periods (AWWA 2008). An obstacle is peoples' general feelings regarding reclaimed water. Technology has been improved throughout the years and helped water reuse to be more socially accepted and affordable.

2.2 Water situation in Namibia

Namibia is situated in south western part of Africa next to Angola, Zambia, Botswana and South Africa, see Figure 1. The country has a population of about 2.0 millions and a low population density (UNDP 2006). The capital Windhoek is situated in the middle of Namibia with 300 000 inhabitants and is functioning as the country's economical centre. Namibia became independent in 1990, earlier it was governed as a colonial country, latest as a province in South Africa under an apartheid authority. Since the independence many things have been changed in Namibia, naturally the water sector has also been changed, for more details see Heyns (2005). According to Heyns (2005) the country has a high Gross Domestic Product (GDP) in comparison to other countries in the southern part of Africa. However, poverty is still a major issue partly because there are some extremely rich people and many very poor. Further, improvements of water supply and sanitation would lead to a better of living in many parts of the country.

Figure 1 Map of Namibia.

In the pre-colonial Namibia, drinking water was obtained from springs and shallow wells. Occasionally, water resources dried up because of severe droughts that periodically affect the country (McDonald & Ruiters 2005). Nowadays, the water resources in Namibia are still scarce, due to its semiarid climate (Flod & Landquist 2010). The potential evaporation, which is between 2400-3800 mm/year (Atlas of Namibia Project 2002), is larger than the potential precipitation of 250 mm/year. Problem with a limited amount of groundwater as well as surface water is present. The access of safe water supplies for domestic water use was 70% for the rural population and 95% for the urban population, in 2005 (Heyns 2005). The water availability in Namibia is only 360 m^3/person/year, which is an estimation based on current population, pumping capacity and full potential of internal water resources. This is a low level compared to 500 m^3/person/year, often recommended by water experts (Heyns 2005).

Different regions of Namibia are today dealing with diverse challenges regarding the water scarcity. According to Heyns (2005) some of these problems are remaining from performance of colonial authorises. A challenge for Namibia is that rural regions with particularly low population density are affected by not having sufficient access to drinking water. In rural areas water conflicts are also present regarding agriculture. Another problem is the trans-border rivers Okavango in the north and Oranges in the south are very valuable drinking water resources, that are shared through negotiation and agreement with neighbouring countries (Heyns 2005). For instance, in 2006 there were negation problems regarding Okavango River with Angola and Botswana. A part of the conflict is that the rivers are also important for fishing and hydraulic power (Shigwedha 2006).

2.3 Water Management and associated issues in Namibia

The ministry of agriculture, water and forestry (MAWF) is responsible for the management and regulation of Namibia's water resources (MAWF 2008). In the Water Supply and Sanitation Policy (WASP) in 2008 MAWF described their prioritizing regarding water use, according to the following:

1. Provision of water for domestic use.

2. Provision of water for economic activities.

Today, challenges in the drinking water management of Namibia are for instance: to achieve sufficient quality of the drinking water, cost effectiveness and higher access of drinking water in the country (du Pisani 2006). In WASP (2008), more specifically, the importance of improving the ground water level in rural areas is discussed and also the problems with a population growth in urban areas, associated with scarce water resources. Generally MAWF's overall goals connected to drinking water supply are to (MAWF 2008):

- Contribute to improved public health.
- Reduce the burden of collecting water.
- Promote community based social development, taking the role of women into special account.
- Support basic water needs.
- Stimulate economic development.
- Promote water conservation.

The aim for the future drinking water supplies in Namibia, described in WASP, is to contribute toward social development and to provide the required environmental infrastructure that enables an economic development. The limited amount of drinking water and the economy development affects each other. One example is mining that accounts for 5% of the drinking water demand (Heyns 2005), its large use of water has been a controversial question. On the other hand, mining might also contribute with an economic growth and has always been subjected to full cost recovery of the water used (Heyns 2005).

Privatization of the water sector in Namibia took place due to problem with funding, according to Heyns (2005). Furthermore he argues how commercialization of the water sector is efficient and provides a better service condition in a long-term. However McDonald and Ruiters (2005), connected to Labour Resource and Research Institute (LaRRI) argues that one consequence might be that the government will increase the emphasis on economy rather than the public's good, regarding the water sector.

Due to the water scarcity and the poverty in the country, water debts are often a reason for criticism as it is a relatively high part of a person's total income in Namibia. Water debts are paid through a tariff block system that divides water usage into blocks, i.e. the price of the water is set according to the consumption (Flod & Landquist 2010). The use of tariff block system aims to promote water conservation. However it is questionable as poor people might be disadvantaged, as more people's consumption might be recognized as one household (Flod & Landquist 2010).

It may be argued that paying for water is the best way of guaranteeing that water will be used in an efficient way even though people do not pay full cost for their water.

However, McDonald and Ruiters (2005) argues that water should be a human right rather than being an important economic trade for the government and gives in *Age of Commodity: Water privatization in southern Africa* (chap. 14) example of where cut offs were made on hospitals and schools due to its failure of paying water debts. Overall water is important and a subject to discussion when it comes to funding.

2.4 Water situation in Windhoek

The drinking water in Windhoek have different sources (see Figure 2), 14% originates from reclaimed wastewater, 74% from treated surface water and 22% from boreholes (Menge et al. 2006). For the reclaimed water there is a blending ratio restriction of 35% in the final blended water (van der Merwe et al. 2005).

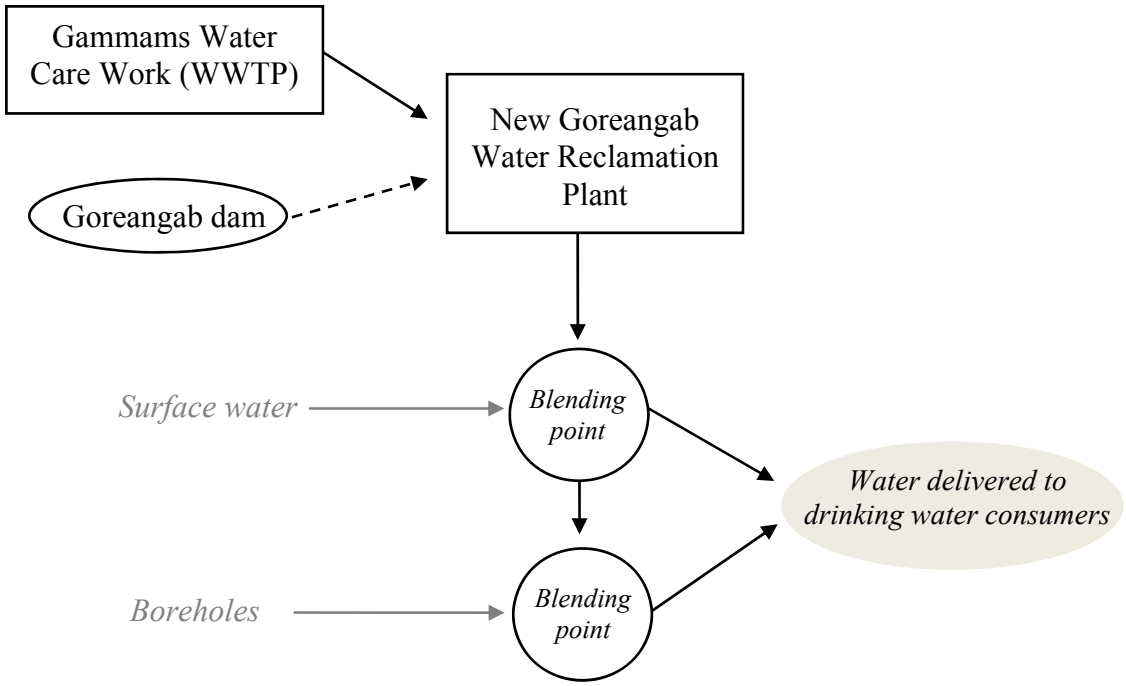

Figure 2 Illustration of the Windhoek water situation.

Direct reclamation of treated sewage to drinking water, was first started in 1968 at Old Goreangab Water Reclamation Plant (OGWRP), in Windhoek. Droughts occurred in the Windhoek in 1992 and 1997 and the required drinking water quality and quantity could not be delivered. One reason was high population growth in the past 100 years that contributed to a more severe situation (Menge 2006). At the time for the droughts the reclaimed water was treated at the OGWRP. The plant was first upgraded and later it was decided to build a completely new treatment plant. In 2001, the New Goreangab Reclamation Plant (NGWRP) was built by the City of Windhoek and it started to deliver drinking water in 2002 (Menge 2006).

The NGWRP is owned by the City of Windhoek but operated by Windhoek Goreangab Operation Company (WINGOC). WINGOC is owned by Veolia (France), Berlin Wasser (Germany) and VA Tech WABAG (Austria).

In 2001, a 20-years management contract was signed between the City of Windhoek and WINGOC, were WINGOC were assigned to be responsible for the operation and to deliver about 21,000 m^3 of water per day (du Pisani 2006).

2.5 Microbiological background

This Master's Thesis considers *Norovirus, Giardia* and *Cryptosporidium* in the risk assessment.

2.5.1 Norovirus

Norovirus infections can cause bowel and stomach infections and common symptoms are vomits and comprehensive diarrhea. Worldwide, *Norovirus* is believed to cause 90% of all non-bacterial and 90% of all epidemics and sporadic bowel and stomach infections (Dalin et el. 2010). It is being transmitted primarily through the fecal-oral route (consumption of faecal contaminated food or water) or through person-to-person spread (Flemming & Lindqvist 2004). When virus genes are measured in water, some genes are viable and can cause infection, others are non-viable. It is discussed how to determine the portion of virus genes that are viable, Rigotto et al. (2011) argues that 1 gene out of 10,000 genes can be considered as viable.

In 2002, *Norovirus* was approved as the official term for the group of viruses that are known as "Norwalk-like viruses" and "small round structured viruses". It is one of the smallest viruses and it has a spherical appearance. Each *Norovirus* is built up by a capsid that covers the genetic material that consists of RNA-viruses (Dalin et el. 2010). *Norovirus* is a part of the Calci virus family and has a genetic material that continuously changes. Therefore, it exist variants with partly different properties. Moreover, *Norovirus* is highly stable and resistant to high concentrations of chlorine (Dalin et el. 2010).

2.5.2 Giardia

Giardia is a protozoan parasite, a parasite is an organism that requires a host animal for survival. *Giardia* can infect humans as well as animals with diarrhoea and the infection is called *giardiasis*. The species of *Giardia* that can infect humans is *Giardia* intestinalis with sub types A and B (Livsmedelsverket 2011). *Giardia* can be spread from animals to humans, the disease is then known as a zoonotic disease. Still, the most significant spread, from a clinical viewpoint, is human-to-human transmission. It might also happen through ingestion of *Giardia* in contaminated water or food.

The risk of infection is increased where hygiene levels are compromised, especially children is a risk group. For instance, in developing countries, children are especially affected where there are disadvantageous community conditions. A risk for those is to suffer from chronic consequences of *Giardia* infection (Thompson 2009).

2.5.3 Cryptosporidium

An international issue in drinking water safety is the risk of waterborne transmissions of *Cryptosporidium* (Carey et al. 2004). There are 20 different species of *Cryptosporidium* but there are mainly two types that can affect humans (Livsmedelsverket, 2011). The first one, *Cryptosporidium parvum* infect both humans and animals and the second one, *Cryptosporidium hominis* infect only humans (Carey et al. 2004).

Cryptosporidium infects the gastrointestinal part of humans and animals and this infection is called *cryptosporidiosis*. Moreover, it is robust and can survive for long time. In Milwaukee, USA 1993 there was an outbreak with more than 400,000 people affected, then the public health consequences of *Cryptosporidium* was realized (Carey et al. 2004).

A problem associated to water treatment is that *Cryptosporidium* (as well as *Giardia*) is requiring extremely high concentrations of chlorine to be inactivated. The required concentrations are much higher than the ones being used in ordinary disinfection of drinking water (Livsmedelsverket, 2011). Consequently, to remove these organisms other barriers are necessary than only chlorine disinfection.

2.5.4 Indicator organisms

In this study, the indicator organisms *Esherichia coli, Clostridium perfringens* and *Somatic coliphages* are used. Indicators organisms were in the past used to show presence of pathogens. Nowadays this is argued, for instance *Somatic coliphages* cannot be used as a suitable indicator for presence of pathogens of faecal origin in surface water, according to Hot et al. (2003). *E. coli* is a widely used and discussed indicator that shows presence of faecal from warm blooded animals. However, there are examples where outbreaks of waterborne pathogens have happened without presence of *E. coli* (Ashbolt et al. 2001).

Some indicator organisms are by Payment & Franc (1993) described as suitable when assessing the virological and parasitological quality of treated drinking water. Moreover spores to *C. perfringens* can also be used for parasitic protozoan cyst or oocyst removal by water treatment (Ashbolt et al. 2001). Moreover, *C. perfringens* is of faecal origin and the main criticism is that *C. perfringens* has a much longer persistence in the environment compared to enteric pathogens. Furthermore, it is important to remember that viruses and other pathogens are not part of normal faecal macrobiotic and is only extracted by infected individuals (Ashbolt et al. 2001). However, there are no correlation between number of indicator organisms and enteric pathogens, according to Ashbolt et al. (2001).

3 New Goreangab Water Reclamation Plant

This chapter describes the New Goreangab Water Reclamation Plant (NGWRP) regarding its history, the multi barrier approach applied at the plant and earlier risk assessments carried out. Furthermore NGWRP's raw water and the treatment processes are described.

3.1 History of Goreangab reclamation plant

Water reclamation was introduced in Windhoek at The Old Goreangab Water Reclamation Plant (OGWRP) in 1968 to avert the water shortages in the region (Haarhoff & Merwe 1995). This was the first place in the world where it was introduced (Law 2003). At the start, in the designing process of OGWRP, three equally important elements to control were identified (Haarhoff & Merwe, 1995):

- Diversion of industrial and potential toxic wastewater from the household wastewater.
- Wastewater treatment to produce an effluent of sufficient quality.
- Adequate treatment at the reclamation plant for production of drinking water.

Throughout the years, the treatment processes of the Goreangab reclamation plant has been continuously evaluated and developed (Haarhoff & Merwe 2006). The OGWRP relied on chlorine as an effective barrier for removal and inactivation of most pathogens. Due to the high additions of chlorine in the water, excessive levels of THM:s (trihalomethanes) were generated (Menge et al. 2007). Furthermore, results from measurements in the final water of *Giardia* and *Cryptosporidium* during the time period 1996-1999, proved incidents of break through. Obviously, the chlorine was not a sufficient barrier against especially *Cryptosporidium* (Menge et al. 2001).

For this reasons, ultra membrane filtration was added into the New Goreangab Water Reclamation Plant (NGWRP) to serve as a safety barrier against *Giardia* and *Cryptosporidium*. It was added as an additional barrier against bacteria and protozoa, to fulfil the criterion of three effective barriers against all pathogens (Menge et al. 2007). Except from ultra membrane filtration, ozonation was added as treatment when NGWRP was designed. Furthermore, on-line monitoring and regularly sampling was also a part of the improvement (Menge et al. 2001). The NGWRP was starting to operated in 2002, but the OGWRP is still in operation and its effluent is today used for irrigation and sport fields[1].

3.2 Multi-barrier approach at NGRWP

Traditionally, drinking water safety was controlled with water laboratory measurements, and then the water was considered safe if the water was proved to be below a certain concentration of organisms or contaminants. A limitation with that method is that it takes time for some of the measurements and it is not possible to cover a complete range of water health concerns.

[1] Jürgen Menge, laboratory chief at City of Windhoek, personal communication May 2011.

Over time, the industry of drinking water has changed to utilize more integrated methods and one example is the multi-barrier approach (Canadian Council of Ministers of the Environment 2004).

By using the multi-barrier approach, the risks involved with drinking water production can be decreased. It aims to protect public health by reducing the risk of contaminated drinking water. The approach involves an implementation of multiple barriers throughout the drinking water system. The approach opens a possibility to make remedial controls more effective. The main strength with the approach is that the failure of one barrier can be compensated by the operation of the subsequent barriers (Canadian Council of Ministers of the Environment 2004).

The barriers should be implemented all the way from the raw water source to the consumers' drinking water tap. Hence, the barriers identified throughout the supply system include other than just the physical barriers (Canadian Council of Ministers of the Environment 2004). There are three different kinds of barriers according to the multi-barrier concept: *non-treatment, treatment* and *operational barriers*. At NGWRP, an example of a *non-treatment barrier* is that the industrial effluents are diverted to municipal drainage areas and discharges. The *treatment barriers* of NGWRP are the physical barriers at the plant introduced to eliminate for instance contaminants or microorganisms. An *operational* barrier is a barrier that can be used as a back-up in case of an unusual event. At NGWRP, powdered activated carbon is an *operational barrier* that is not normally used (van der Merwe et al. 2005).

3.3 Earlier risk assessment results of NGWRP

There has been continuously research and investigations performed at the OGWRP and the NGWRP. One of them was TECHEAU an integrated project founded by the European Commission, under the Sustainable Development, Global Change and Ecosystems Thematic Priority Area. Within the project, a case study of NGWRP was performed. The case study included a risk assessment with a coarse risk analysis called Hazard Analysis and Critical Control Points (HACCP). It was performed with a risk ranking approach that included the entire system, from the raw water to the finalized water. The result indicated that there were main risks with the raw water and the monitoring of the treatment processes. Another main risk was identified as chemicals for the treatment. The major risk was identified as failure of the treatment processes at NGWRP (Swartz et al. 2010).

Moreover, in the TECHNEAU case study a more in detail risk analysis was performed as well. This was performed with a Fault tree analysis (FTA), but only for the conventional treatment process (Swartz et al. 2010). This Master's thesis is a continuation of the FTA started within the TECHNEAU project, to finally encompass the whole treatment system. Still, it was not a part of the TECHNEAU project.

The FTA was performed for the conventional treatment including coagulation, dissolved air flotation and rapid sand filtration. The fault tree method was proved to be a useful method when analysing probabilities of failure of treatment processes in drinking water plants. Furthermore, the result indicated that the probability of failure in the conventional treatment process were low.

To evaluate the consequences of the failures identified in the FTA, there was a proposal to combine the result with a QMRA (Swartz et al. 2010).

3.4 The treatment processes at NGWRP

The raw water at the NGWRP is received from the wastewater treatment plant (WWTP) Gammams Water Care Work (GWCW). The main processes that treat the water are coagulation, dissolved air flotation (DAF), rapid gravity sand filtration, ozonation, biological- and granular activated carbon (BAC, GAC), ultra membrane filtration (UF) and chlorination, see Figure 3. The plant is operated and monitored with the Supervisory Control and Data Acquisition Centre (SCADA) and also monitored by operators. If there is a failure or problem with the treatment, the water can be re-circulated to the beginning of the treatment train. This is possible after the ozonation, the GAC and after the chlorination. It is often performed after the ozonation but seldom after the chlorination[2]. Furthermore, it is also a possibility to reject the water instead of re-circulation.

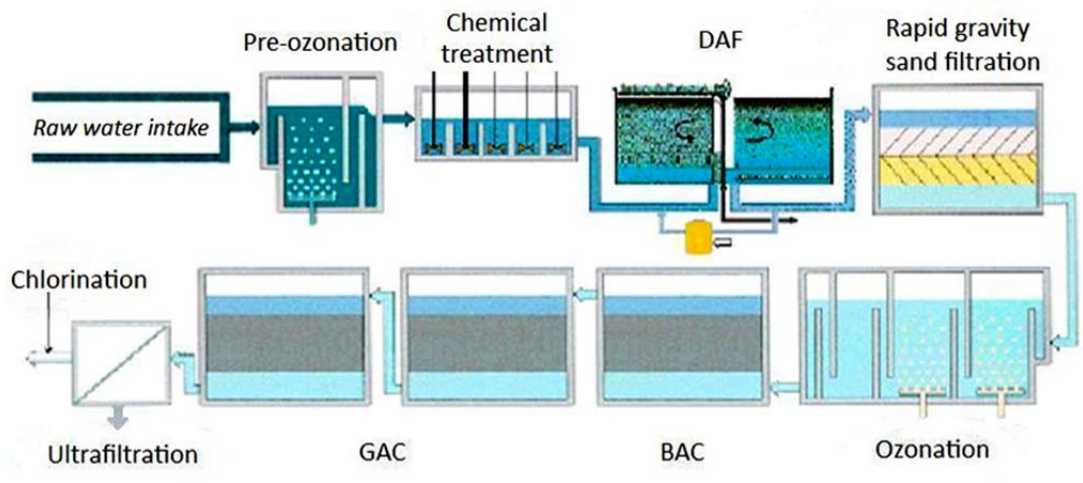

Figure 3 The treatment processes at NGWRP (With permission from WINGOC 2011).

The treatment steps at NGWRP are barriers where some are considered as microbiological. In this study, *Norovirus*, *Giardia* and *Cryptosporidium* were investigated and the barriers have different efficiency against the pathogens, see Figure 4.

[2] Siegfried Mueller Process, Research and Technical Manager WINGOC, personal communication May 2011.

- *Norovirus:*
  - Barrier: Conventional treatment
  - Strong barriers: Ozonation, UF and chlorination
- *Giardia:*
  - Barrier: Conventional treatment and chlorination
  - Strong barriers: Ozonation and UF
- *Cryptosporidium:*
  - Barrier: Conventional treatment and ozonation
  - Strong barrier: UF

Figure 4 The microbiological barriers for each pathogen investigated in this study. The strong barriers indicate that their efficiency regarding removal/inactivation is strong.

3.4.1 The raw water source

NGWRP's raw water is taken from either the Goreangab Dam or the maturation pond that receives effluent from the wastewater treatment plant GWCW. The two sources can be mixed or used separately to optimize the quality (Menge 2006). At present, the raw water is taken from the GWCW's effluent (wastewater treatment plant, WWTP) due to problems related to contamination of industrial effluent in the Goreangab Dam[3].

The GWCW consists of primary settling and anaerobic digestion with drying beds. Further on, the water is divided into two streams. The first stream is bio filters with settling and maturation ponds. The second stream is biological activated sludge followed by maturation ponds. Altogether about 33 Ml/day is treated at GWCW (Menge 2006), this is a higher flow than the plant was designed for[4]. The quality of GWCW's effluent is considered to affect the NGWRP and problems have been present due algae and not acceptable concentrations of ammonium that affects the performance of the processes negatively[5].

[3] René Mertens Operator Manager WINGOC, personal communication May 2011.

[4] Jürgen Menge, laboratory chief at City of Windhoek, personal communication May 2011.

[5] James Villet, Chemical technical developer WINGOC, personal communication May 2011.

3.4.2 Pre-treatment

First the raw water passes through the blending and then if needed the powder activated carbon (PAC) can be used as a back-up if the ozone or another process fails, but it happens very rarely. If the PAC is applied, it removes taste, odour and strongly absorbed pesticides and herbicides (Crittenden el al. 2005, chap 15). It works similar as activated carbon, but PAC provides a larger surface area.

The first or the second treatment step for the raw water is the pre ozonation which constantly is applied and described further in chapter 2.7.4

3.4.3 Conventional treatment

After, the water is transported to the chemical treatment. The chemical hydrochloric acid (HCl) is dosed over the first weir, but that is generally not considered as necessary. The primary coagulant ferric chloride ($FeCl_3$) is added over the second weir (WINGOC 2001). The water is then transported to two basins where chloride enhances the coagulation for organic removal (Swartz 2010). It is a process where the free chloride hydrolyzes rapidly and forms insoluble precipitates and particles aggregate (Crittenden el al. 2005, chap. 8). After the coagulation, there is an electronic flow meter and a possibility to add polymer, which is only applied when there is a poor raw water quality. A second stage is where the water goes through a flocculation tank and gentle or no agitation is applied and smaller particles can aggregate. The coagulation and its overall performance are affected by parameters such as pH, reaction time, temperature and ionic strength (Crittenden el al. 2005, chap. 8).

After the chemical treatment the water passes through the dissolved air flotation (DAF), to flocculate and separate solids from the water. Its efficiency depends on the coagulation process (Crittenden el al. 2005, chapter 10.7). DAF is regarded as effective for water with algae, dissolved organic matter and low temperature water. There are two important parameters due to its function: bubble size and bubble size velocity. In the basin it is important that the hydraulic conditions are suitable (Crittenden el al. 2005, chapter 10.7).

At NGWRP, the DAF is regarded as the "heart" of the reclamation plant (Swartz 2007). DAF is a process where air bubbles of compressed air, so called "white water", are introduced to create flocks. The "white water" is created in an air saturator where pumps compress air (WINGOC 2001). The "white water" is then introduced into the DAF process with distribution pipes with nozzles. While the "white water" is moving upwards, it attaches flock particles and is causing them to create floats on the surface (Crossley & Valade 2006). The flock particle forms a foam layer, also known as floats. The floats are removed with a weir about every second hour, but the removal frequency is due to water conditions.

Apart from the float creation at the surface, there is sedimentation created at the bottom, which is removed by gravity around every eight hour[6] (WINGOC 2001).

[6] James Villet, Chemical technical developer WINGOC, personal communication May 2011.

The water is then transported and caustic soda (NaOH) is dosed over a motorised weir to raise pH and also, permanganate (MnO_4) is added for instance to accelerate oxidation of iron and manganese (WINGOC 2001).

The water is then equally distributed over five rapid gravity sand filters. The rapid sand filtration contains anthracite, a naturally occurring coal substance. There is also a layer of sand at the bottom. The process aims to oxidise and absorb iron, manganese and smaller suspended solid particles. The rapid gravity sand filtration aspires to maximize removal of *Giardia* and *Cryptosporidium* (Menge 2006).

Properties of the filter, such as grain size, size distribution, density, shape, hardness, bed porosity and specific surface area are all important parameters due to the filter performance (Crittenden el al. 2005, chap. 11.2). In order to avoid head losses and to achieve a good performance, rapid gravity sand filtration is regularly backwashed with air, combination of air and slow rinse water and high rinse water. At NGWRP, there is also a possibility to dose chlorine powder by hand if needed[1]. The backwashing process is important, fine needs to be removed but also to avoid stratification of the layers. Due to risk of lost performance, the first filtrate after backwashing is rejected (WINGOC 2001).

3.4.4 Ozonation

Ozone (O_3) is in general added in drinking water production for taste and odour control, disinfection and oxidation. Furthermore, it is the strongest oxidants in comparison to chlorine dioxide, combined chlorine and ultra violet (UV) light. The ozonation is also becoming more common (Crittenden el al. 2005, chap. 13.7). At the NGWRP, the ozonation process aims to oxidize organic compounds, remove iron and manganese and inactivate bacteria, viruses and protozoa (WINGOC 2001). Regarding, microbiology disinfection in general, ozone is very effective towards *Giardia* but less towards *Cryptosporidium*.

The O_3 is produced before it is dosed at NGWRP. Problems often associated with ozonation are by-products such as bromate (BrO_3^-) and other issues are for instance stripping of volatile (Crittenden el al. 2005, chap. 8.5.) Bromate is regarded as a problem due to its potential carcinogenicity (Crittenden el al. 2005, chap. 18.6). O_3 is a gas that in the water creates free radicals with high oxidative ability and is therefore used as a compound to increase the oxidation rate. For the process, pH adjustment is important as it affects the amount of needed O_3 in the reaction (Crittenden el al. 2005, chap. 8.5.)

The O_3 is produced on site, with two major steps. The first step is to create a high oxygen gas (93% pure O_2) (Menge 2006). To produce high purity O_2 gas, the air is compressed by two compressors and a third is in standby mode.

Within the air process it is crucial that the air quality is sufficient, therefore the air is filtrated and dried (WINGOC 2001). The compressed air is then transported to the pressure swing (PSA) which can be described as an absorb vessel containing synthetic zeoliten molecular sieve (ZMS) (WINGOC 2001). The process includes a “swing” whereas the tank is changing between absorption of nitrogen and a regeneration phase

where pure oxygen is produced. After each PSA plants the purity as well as flow, pressure, temperature and dew points are monitored (WINGOC 2001).

The second step in the ozonation process is to produce O_3 from the O_2. This is performed by first lowering the pressure in the generators. The transforming process takes place in a so called corona discharge. Simplified it can be described as a high voltage electrical discharge that transform O_2 to O_3 (WINGOC 2001). To enable the transforming process a chiller unit is essential to keep the ozone at a sufficient temperature. Before it passes its dosage points to the water the O_3 gas is analyzed. Outside the chambers in the air a censor is provided to monitor leakage, primarily as a safety monitoring for staff (WINGOC 2001).

The production of O_3 at NGWRP is located at one place; however the dosing of O_3 takes place at three stages as pre-, main- and off gas- ozonation. The main dosing also involves addition of hydrogen peroxide (H_20_2). If not all O_3 is used it needs to be removed with a vent ozone destructor (VOD) that destroys it and deposit the O_2 to the air (WINGOC 2001).

The main ozonation consists of a tank divided into three sections with individual possibilities of O_3 being dosed in a plug flow movement, the gas flow is also measured and controlled (WINGOC 2001). The first chamber (A) provides a dosage of 9-10 mg O_3/l, the second chamber (B) a dosage of about 2-5 mg O_3/l and the third chamber (C) is mainly a reserve. The amount of O_3 needed is controlled by detecting leftover residual ozone in the water (WINGOC 2001). The residual ozone depend on the amount of dissolved organic carbon in the water (DOC) (1-1.5 mg O_3/mg DOC). Moreover O_3 is introduced into a water side stream with booster pumps and finally a radial diffuser injects the O_3 into the water (WINGOC 2001).

The pre-ozonation is introduced before the screen and is constantly in use but is not considered as a barrier itself. The O_3 is introduced into side streams, generated by booster pumps, after the water is mixed and injected in the pre-ozonation chamber (WINGOC 2001).

The O_3 in the off gas re-injection is the leftover O_3 from the main ozonation and is introduced with an eductor into a side stream. Off gas re-injection is primarily applied to assist the oxidation (WINGOC 2001).

The hydrogen peroxide (H_20_2) is dosed in two places for different reasons. The first dosage is to increase the oxidation in the main ozonation. More importantly, the second dosage is to remove residual ozone to protect the biological activated carbon steps (GAC/BAC). Otherwise, the micro-biological culture can be destroyed (Menge 2006).

3.4.5 Bacteriological activated carbon and granular activated carbon

The bacteriological activated carbon (BAC) comes after the ozonation. It consists of seven filters and aims to reduce the organic load in the water.

In the ozonation process, the organic constituents have had an extensive oxidation; consequently the organic constituents are in a more easily biodegradable form when it reaches the BAC treatment step. On the activated carbon, there will be a culture of micro-organisms established that will consume the bulk of these organic constituents.

The water is transported with up-flow in the BAC filters, i.e. it enters at the bottom and leaves at the top of the tank (WINGOC 2001).

It is favourable to have the BAC process before the granular activated carbon (GAC) filters (WINGOC 2001). The larger fraction of the organic load is reduced at the BAC step and the smaller fraction of the organic constituents is reduced at the GAC step. In this way, BAC filters can often extend the life of GAC filters with 4-8 times (WINGOC 2001). Even though these processes are not considered as microbiological barriers, they are seen as important treatment steps for the water quality.

Granular activated carbon (GAC) works by having a large surface area of carbon where molecules can be adsorbed. The GAC consist of a primary and a secondary filter. The primary filter is run with up flow and is seen as the rough filter that removes the bulk of the organic matter. The secondary filter is performed with down flow and is considered as the final polishing stage of the GAC process (WINGOC 2001).

There are seven GAC filters and the process is important for the water quality as it remove dissolved organic compounds, colour, taste and odour (WINGOC 2001). Throughout the GAC process, there is a biological activity where microorganisms are constantly reproduced. Furthermore GAC also have the potential to remove specific micro pollutants, bromate, ammonium, pesticides, herbicides and tetra-chloromethane. Another perspective is that it in general also acts as a buffer against the effect of toxic organic. As with other filtration processes particle size, particle composition and surface properties are important for the filter efficiency (Crittenden el al. 2005, chap. 15.6). In order to achieve sufficient performance, backwashing is performed on a timer basis about every second week, moreover old filters are removed and regenerated[7].

3.4.6 Ultra membrane filtration

Ultra membrane filtration (UF) is a treatment process that aims to remove particles larger than 0.05 µm. The membranes are built up of thin walls of porous material with an asymmetric structure, see Figure 5. It can be described as a "continues mass with tortuous interconnection voids" (Crittenden el al. 2005, p. 963.) There are many things to consider for the overall capacity of the UF e.g. surface properties of the filter, surface chemistry and pore charge (Crittenden el al. 2005, chap. 12.4).

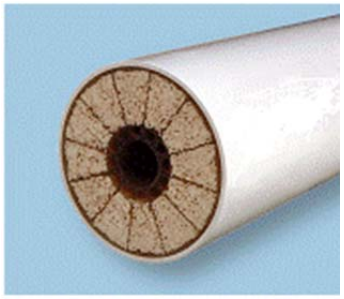

Figure 5 UF membrane element (Norit Membrane Technology 2011).

[7] Siegfried Mueller Process, Research and Technical Manager WINGOC, personal communication May 2011.

After a while, when UF membranes are in use, it will be a loss of performance since solids are accumulated on the filter media and particles are clogged. This can lead to fouling which can be expressed as cake formation, pore sealing and internal pore constriction (Crittenden el al. 2005, chap. 12.5.). To avoid these performance losses, backwash of the membranes are needed as well as cleaning with chemicals. These different cleanings are often performed in cycles, after a certain running period of the UF membranes.

The UF process at NGWRP consists of 6 racks that each contains 14 membrane modules (see Figure 6), in total the membrane area is 13,440 m^2 (WINGOC 2001). The water on the feed side is called retentate and the water that is being filtered through the modules are called permeate. The first stage of the UF system is the membrane feed sump where there is a possibility to add chlorine to the retentate for a disinfection purpose. The membrane feed pumps press the retentate through the membranes, and as the permeate passes, caustic soda (NaOH) is added for pH adjustment and for a cleaning purpose.

Figure 6 A membrane rack with membrane modules. Photo: Helen Ander.

UF is operated with dead end mode at NGWRP which is also known as direct filtration (WINGOC 2001). This means that lower energy consumption is required and that the membranes can be operated at a lower pressure drop compared to other flow systems e.g. a cross flow system. In order to monitor and assure that the UF process is working optimal, the process is supervised by the central control system SCADA and each rack also has a local control cabinet. The programmable logic controller (PLC) controls the UF racks and assures maximum capacity and minimal fluctuations.

Furthermore, to clean the membranes there are three different cleaning strategies: backwashing, chlorine cleaning and acid cleaning (WINGOC 2001). The backwash is performed with clean permeate that is taken from the final water. The backwashing is distant-controlled and performed regularly about every 30 minutes, and it is operated with two backwash pumps[8]. Additionally, backwashing is performed when the trans-membrane pressure is exceeded or if it is manually initiated.

[8] Siegfried Mueller Process, Research and Technical Manager WINGOC, personal communication May 2011.

After about 14 backwashes, chlorine cleaning is initiated with distant-controlled performance[2]. Sodium hypochlorite (NaOCl) is being added to the backwash water with a dosing pump and is then pumped through the membranes. This aims to remove all microbiology and to disinfect the membrane surfaces. When the chlorine cleaning has been performed about 4 times[5], an acid cleaning will be run with hydrochloric acid (HCl) that is added to the backwash water in the same manner as with the chlorine cleaning. This process removes insoluble salts and performs removal of scale from the membrane surfaces (WINGOC 2001).

These different chemical cleanings can as well be manually initiated when necessary (WINGOC 2001). After the different cleaning processes there is a flushing with permeate to assure that the chemical concentrations and pH level are acceptable in the membranes.

3.4.7 Chlorination

The last barrier at NGWRP is chlorination, where chlorine gas (Cl_2) is dosed. Generally Cl_2 exists in two forms in water, hypochlorite (OCl^-) and hypochlorous acid (HOCl), the later is more effective concerning inactivation of pathogens (Ødegaard, 2009). A lower pH is preferable as it leads to a higher concentration of HOCl. Furthermore, the contact time affects the chlorination process as a longer contact time will increase the inactivation of microorganisms. At NGWRP, the aim is to have a pH of 7.8-8.2, a contact time of one hour and a residual chlorine concentration of 0.9-1.2 mg/l. The residual chlorine is measured at the outlet of the chlorination tank (WINGOC 2001). A method called breakpoint chlorination is applied at NGWRP, which means that chlorine is added to the level where the reactions between chlorine and compounds in the water no longer decrease the chlorine concentration. When the breakpoint is reached, the effectiveness of the chlorination will increase (University of Pretoria 1996).

4 Method

In this chapter, it is given an overview of risk management and how Quantitative microbial risk assessment (QMRA) and Fault tree analysis (FTA) can be combined. Moreover, the theory of the methods FTA and QMRA are described.

4.1 Overview of the risk management process

Risk management generally consist of three parts: risk analysis, risk evaluation and risk reduction/control. Risk analysis is about identifying hazards and estimating risk levels. Moreover, risk evaluation is when the estimated risk levels are evaluated or ranked. The last step is risk control when decisions are being made concerning risk reducing countermeasures. It can schematically be presented with a generic framework; one example is shown in Figure 7 which is specific for the water risk management.

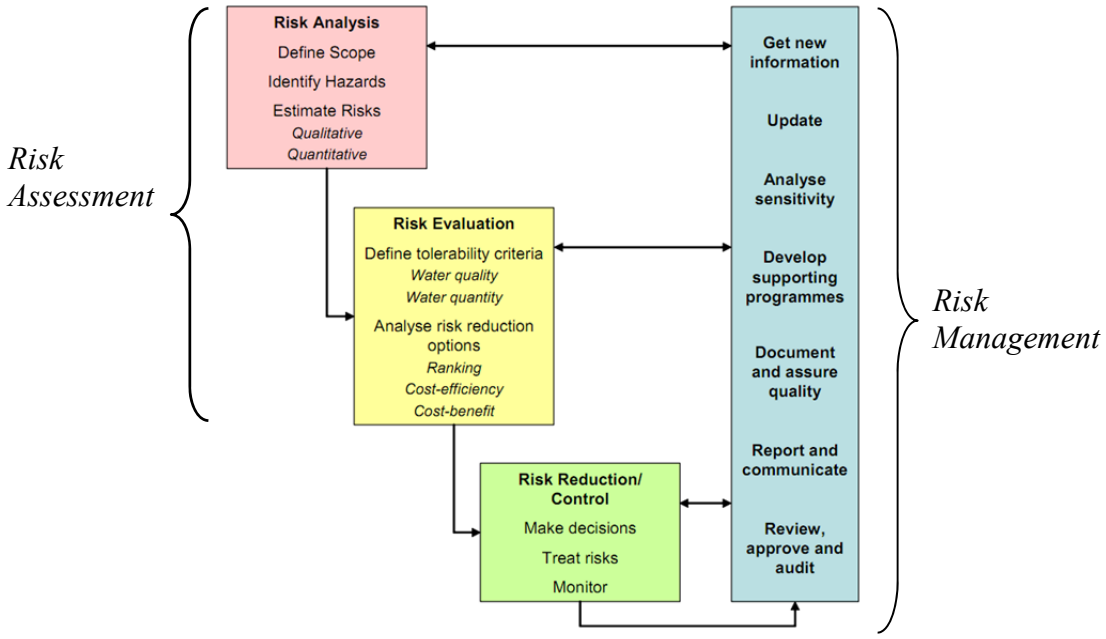

Figure 7 *The TECHNEAU generic framework for water risk management (Rosén et al. 2008).*

The generic framework concept was applied in this Master's Thesis when assessing the microbiological risks at NGWRP. The concept was applied with a FTA and a QMRA model, but adjusted according to Figure 8. To identify hazards in the system and to calculate the probability of microbiological failure (P_F), a FTA was performed for the treatment processes at the plant.

To evaluate the consequences of possible failures at the plant, a QMRA was performed. Eventually, P_F and the QMRA results were integrated (with equation 3.4) to obtain the annual probability of infection (P_I) for different scenarios. The FTA and the QMRA together contribute to the risk analysis. To evaluate if the risk levels were acceptable, P_I was compared with the generally accepted health based target value of 10^{-4} annual probability of infection, which was the risk evaluation phase (Medema & Ashbolt 2006). The result was evaluated and possible countermeasures were discussed and proposed (risk reduction/control).

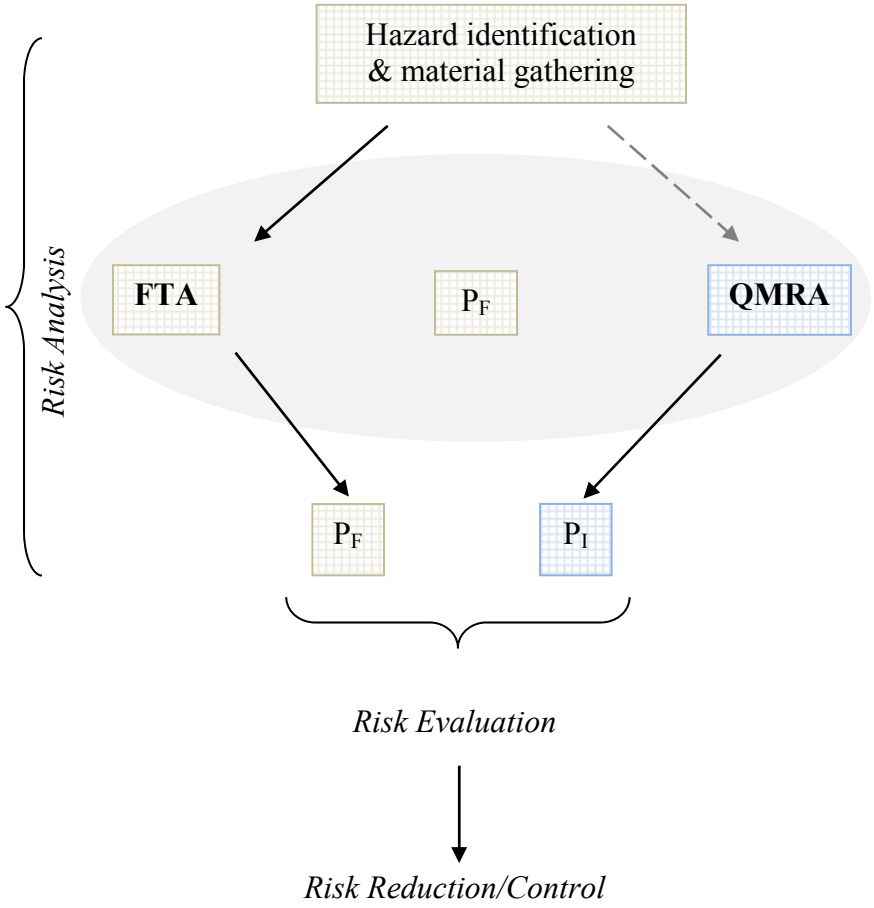

Figure 8 Schematic description of the method applied in this Master's Thesis.

4.2 Fault tree analysis

A fault tree describes how failure events can occur, how they might interact with other events and finally result in an overall system failure. The fault tree technique was introduced at Bell Telephone Laboratories in 1962, when a missile system was launched (Rausand & Høyland 2004). Nowadays, the fault tree method is used in many areas when evaluating systems' reliability e.g. chemical systems, railway industry and software systems (Cepin & Mavko 2001). It is commonly used for risk and reliability studies (Rausand & Høyland 2004). Fault tree analysis (FTA) enables identification of possible design improvement strategies (Burgman 2005) and it can be used to model risk-reduction measures.

There are static fault tree analyses where the order of the events does not affect the outcome. In dynamic fault trees, on the other hand, the order of the events does influence the outcome. Dynamic fault trees are characterized by logic gates and that open the possibility to model systems with the ability to compensate for failures (Lindhe 2010).

One possible approach to solve a dynamic fault tree is to translate it into a Markov model. In a Markov model, the transition between the state that the component work and the state that it does not work is described with a repair rate (μ) and a failure rate (λ). The probability of failure (P_F) can be calculated with μ and λ, according to equation 3.1 (Lindhe 2010).

$$P_F = \frac{\lambda}{\lambda+\mu} \tag{3.1}$$

$1/\lambda$ is defined as the "mean time to failure" (MTTF), also called uptime, and $1/\mu$ is defined as the "mean downtime" (MDT), also called duration of failure, see Figure 9. The uptime represent the time when there is no failure with a specific component in a system and the downtime is the time the failure last for (Lindhe 2010).

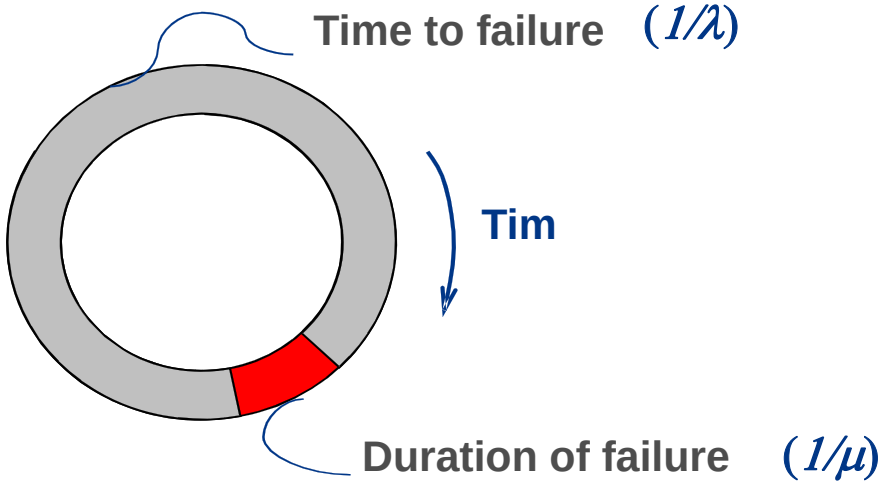

Figure 9 Description of 1/λ and 1/μ (Lindhe 2010).

4.2.1 Theoretical performance of FTA

Fault trees are constructed with a top event that typically represents system failure. On the bottom of the tree there are basic events that may lead to the top event. In-between the top event and the basic events, there are intermediate events that describe the connections between them. Fault trees are created with branch points that consist of logic gates e.g. AND-gates and OR-gates. Standard symbols used in FTA can be seen in Figure 10.

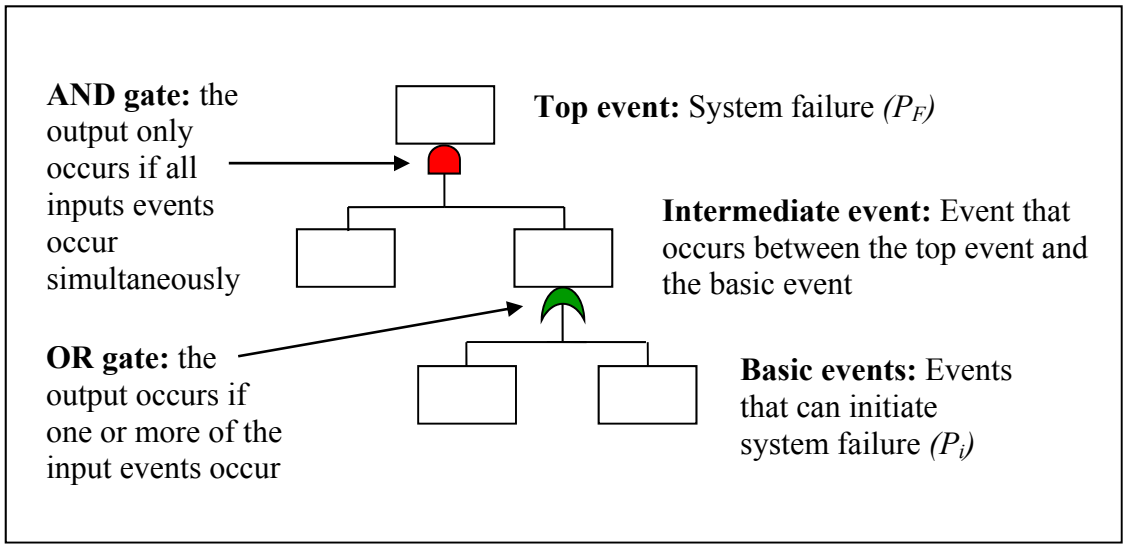

Figure 10 Description of symbols used in fault trees.

A FTA can be performed as a qualitative and/or as a quantitative study. However, qualitative assessment does not involve data for the different events and can instead be performed by evaluating the fault tree's structure and appearance. It can be carried out on the basis of the cut sets of the fault tree, a cut set can be defined as a set of basic events whose occurrence ensures that the top event happens. These different sets can then be ranked based on specific criteria and the fault tree can be evaluated (Rausand & Høyland 2004).

Quantitative FTA involves data for the basic events e.g. failure rate (λ) and repair rate (μ) and with calculations, corresponding data for intermediate- and top-events are calculated (Rausand & Høyland 2004). This requires collecting of input data that can be a time consuming.

The probability of failure for an event depending on an OR-gate or an AND-gate can be calculated with equation 3.2 and 3.3 respectively. P_F is the probability of failure for an event and can be calculated with the sub-ordered events' probability of failure (P_i) (Lindhe 2010).

$$P_F = 1 - \prod(1 - P_i) \qquad \text{OR-gate} \qquad (3.2)$$

$$P_F = \prod P_i \qquad \text{AND-gate} \qquad (3.3)$$

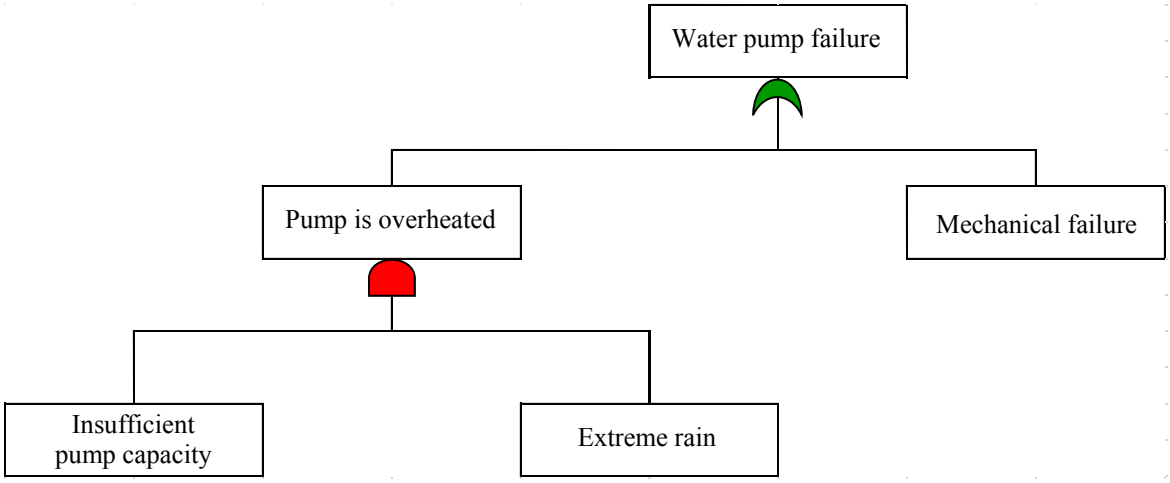

Figure 11 Example of a FTA when there is a water pump failure.

An example of a fault tree illustrating a water pump failure can be seen in Figure 11. Fault trees are often created during structured brainstorming sessions where hazard identification is carried out. This can be performed by different experts that together define the hazardous events. Information about the events can be obtained from historical monitoring failure data or when not available, data can be based on expert judgements (Lindhe 2010).

When evaluating the result of a fault tree it is important that all parts of the tree are considered, not only at the top level. Failure rates, failure probabilities and downtimes are important in all parts of the tree (Lindhe 2010).

4.2.2 Uncertainty and sensitivity analysis

Within a risk assessment many uncertainties are present and must therefore be considered in the risk assessment. Lindhe (2011) states that proper analysis must involve uncertainties of identified probabilities and consequences.

Failure events can be described with a probability distribution in a FTA (Gentry 2007), where assumptions are taken into consideration. To describe λ and μ in the model, Gamma distributions can be applied, as it only consider values above zero and easily can be updated. Moreover, it is possible to have a variation in their shapes (Lindhe et al. 2009). The calculations in the FTA are performed with Monte Carlo (MC) simulations that by random simulate numbers from the distribution representing the input variables. It is an iterative process and can for example include 10,000 iterations. All models have uncertainties and one way to include these are MC simulations. It allows an analysis of the uncertainties in the results based on uncertainties in the input data (Lindhe 2010).

According to Rosen et. al (2010), MC simulations can provide sensitivity analysis as a contribution to the total uncertainty analysis. The sensitivity of the model can be analyzed by ranking what contributes most to the uncertainty, the result can for example be presented with a rank correlation coefficient. The parameters with the highest rank correlation coefficients are contributing the most to the result and may be studied more in detail as they affect the final result the most (Lindhe 2011).

4.2.3 Limitations of FTA

There are some limitations that need to be taken into consideration when using the dynamic fault tree method. A fault tree can become large and cumbersome and consequently difficult to handle and too much work might be required for it to be useful (Burgman 2005). Furthermore, the result must be analysed carefully. There might be the same probability of failure for two events even if the uptimes and downtimes differ. One way to handle this is to analyse the results in combination with information about the system's behaviour (Lindhe 2010).

4.3 Quantitative microbial risk assessment

Within risk management of drinking water, various tools and methodologies are used, whereas one is Quantitative Microbial Risk Assessment (QMRA). It is argued that "*QMRA can provide an objective and scientific basis for risk management decision"* (Medema & Ashbolt 2006, p 8). QMRA is a method to perform risk assessment reflecting health risks for the consumers. It is performed to validate current performance and develop future plans (Howard & Pedley 2006). For instance QMRA can be performed to asses health based targets and to evaluate risks described in the Water Safety Plan (WSP) (Petterson et al. 2006).

To perform a good model with reliable outcomes it is central to apply sufficient data. The data might come from experiments, review of existing data or from literature (Lundberg Abrahamsson et al. 2009). It is important that data from literature is adjusted to area specific situations (Howard & Pedley 2006).

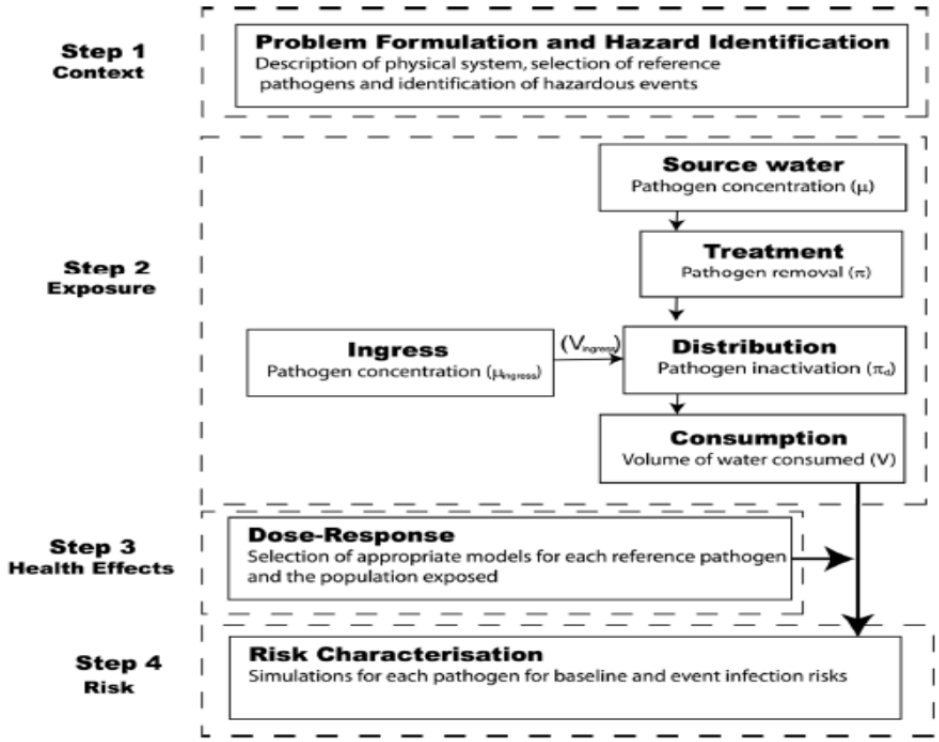

Figure 12 Model of different steps in QMRA (Petterson el al. 2006).

4.3.1 Theoretical performance of QMRA

To perform a QMRA model, different steps are required and the steps from the QMRA methodology are described in Figure 12.

The first step is to perform a problem formulation and hazard identification (Petterson el al. 2006). This problem formulation and hazard identification will create the base of further steps in the process.

The second step is to define the exposure and consumption for the people, the water source and the treatment at the plant. The treatment efficiency is essential regarding its effectiveness and removal of pathogens. QMRA Methodology (Petterson et al. 2006) discusses every treatment plant's very individual performance and also how treatment efficiency is a crucial parameter for the overall performance. For the raw water, Gamma distributions can be used which describes the probability distribution of positive values expressed by a shape and scale coefficient, there are also other possible distributions to describe the raw water more or less suitable (Pettersson et al. 2006).

The amount of water consumed by a person is a parameter used in the QMRA and is described in "*Estimation of the consumption of cold tap water for microbiological risk assessment: and overview of studies and statistical analysis of data (2007)"* where different studies are compared. Their discussions include the variations between developing and developed countries and also if boiled water should be taken into account, as it is generally not considered as drinking water. Their findings conclude that it would be best to use country specific data, if it exists. Their final recommendation is a conservative value of 3.49 glasses per day (1 glass = 250 ml) (Mons et al. 2007).

Generally, programs created with the QMRA methodology often offer the possibility to use default values for some of the process treatment steps, raw water concentrations and local illness frequency (Petterson et al. 2006). The default values can be used when there is no other information available.

The third part is to evaluate health effects with the dose response concept, which involve appropriate distributions of pathogens and the exposed population. The dose-response represents how many pathogens in drinking water that may lead to infection of the population. To estimate these parameters, information from outbreaks has been used (Petterson et al. 2006). Selection of appropriate models for each reference pathogen and the population exposed is important. The dose response relationship is an exponential model, also the Beta Poisson distribution is sometimes applied for describing the dose-response in QMRA (Petterson et al. 2006).

The fourth step is risk characterization which aims to describe expected health outcomes of the population (Petterson et al. 2006). This is expressed as probability of infection based on the result from QMRA modelling, where the systems' different performance together and separately (each treatment step) will be used. The overall probability of infection is a binomial process, the simplest model also assume that all pathogenic particle within a host has the same constant probability of survival (Petterson et al. 2006).

The result is often compared with the health based target taken from USEPA where a critical level of infection is 1/10,000 of exposed people / year (also written as 10^{-4}) (Lundberg Abrahamsson et al. 2009). Also Medema & Ashbolt (2006) describe it as a value to use for annual infection and also a starting point for a for risk management process. Within the health based target infection is defined as pathogens surviving host barriers and actually growing (Petterson et al. 2006). It could be added that an infection is not the same as being ill or cause a disease

An expression to obtain the annual probability of infection *(P_I)* is described with equation 3.4, the exposures are assumed to be independent (Pettersson et al. 2006). Furthermore, the formula is described with a time horizon of one year.

$$P_I = 1 - ((1 - P_{\inf(normal)})^{t(normal)} \prod_{i=1}^{n} (1 - P_{inf(n)})^{t(n)}) \qquad (3.4)$$

$P_{inf(optimal)}$ = daily probability of infection under optimal process operation
n = is the total number of event conditions to be included
$t_{(optimal)}$ = days throughout the year under optimal process operation
$t_{(n)}$ = days throughout the year under an event condition

Finally, how the infection may cause symptom of illnesses must be evaluated together with likelihood, severity and duration. (Petterson et al. 2006).

What to aim for in a risk assessment is no infection, however the cost aspects will in reality be taken into consideration. Therefore the ALARP model can be used which is As Low As Reasonably Practice, defined as the zone between acceptable and non-acceptable (Lundberg Abrahamsson et al. 2009).

4.3.2 Limitations of QMRA

In the QMRA when modelling process it is important to consider variability and uncertainty and also to understand that QMRA is an idealization (Pettersson et al. 2006). As discussed a very crucial step is to find sufficient data and to understand its uncertainty. In (Roser et al. 2006) they are also discussing that probability density function (PDF) does not account for all sorts of variance.

Another problem is to find suitable reference pathogens, as it should be an organism whose severity of impact would be similar to pathogens that is controlled (WHO 2004). However, Howard and Pedley (2006) state that assumptions regarding relationships between indicator organisms and pathogens are necessary to be able to perform a model. Moreover pathogens' sub-population may not be totally recognized in the model (Roser et al. 2006). Also for the treatment capacity the predicted hydraulic flow might be an issue, but is not considered in the QMRA methodology (Roser et al. 2006).

In developing countries other issues are more current than for developed countries. For example in a case study in Kampala, Uganda, written by Howard and Pedley (2006), it is noticed that the present immune status of the people is of great importance in developing countries and finding those values might be difficult. However, in their conclusion they found QMRA feasible for developing countries but stresses that assumption throughout the study must appear realistic.

However a weakness with QMRA identified in the case study was that water borne infections is hard to distinguish from infections caused by poor hygiene and food (Howard et al 2006).

Something to take into consideration is that a large portion of the people in Namibia suffering from HIV/AIDS (Howard & Pedley 2006). For example *Cryptosporidium* is often associated with diarrhoea and studies show a higher mortality rate if the consumers are HIV positive. Also Rotavirus is considered as particularly severe for HIV/AIDS infected people.

5 Analysis

In this chapter it is described how the FTA and QMRA methods were applied at NGWRP. What adjustment needed to be performed for the model and how the estimations were made.

5.1 Dynamic fault tree analysis at NGWRP

This chapter explains how the quantitative FTA was performed at NGWRP (the theory of the method is described in chapter 4.2) which involved workshops where fault trees of the treatment processes were constructed. Furthermore, the dynamic FTA involved conducting and estimating of data for the model, calculation of data and finally an evaluation of the result.

5.1.1 The workshops in the FTA

The workshop group consisted of different kind of experts for example a process developer, a process technician, an expert that was involved in the initial design of the plant and a consultant that was a former employee at WINGOC. There were three workshop meetings held during a period of 5 weeks. Initially, it was important that the group had a basic understanding of the FTA method.

The workshop focused on construction of the process fault trees through discussion, particularly with people that had a more detailed understanding of the processes. It was an iterative process, where the structure was changed as a deeper understanding amongst the group was obtained of the processes and the fault tree method.

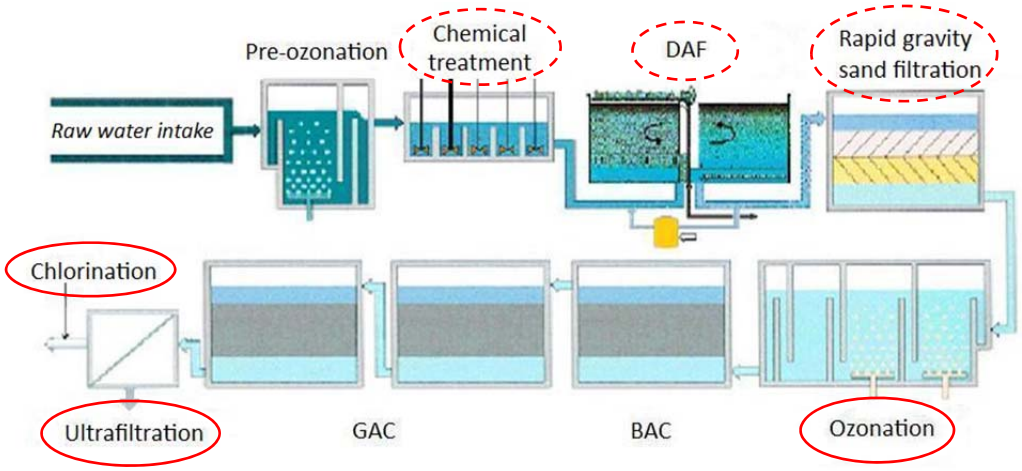

Figure 13 In this Master's Thesis, fault trees were constructed for the process marked with red circles. For those marked with crosshatched red circles fault trees were constructed in an earlier risk assessment.

It was decided that the ozonation, UF and the chlorination should be studied in this Master's Thesis, see Figure 13. However, the fault tree of the conventional treatment (chemical treatment, DAF and rapid sand filtration) was created in a previous research project (Swartz et al, 2010), see Appendix V, which was added to the complete fault tree that was created in this study.

However, it was concluded to not consider the GAC, BAC and pre-ozonation process in the study as these are not considered as critical barriers for the microbiological removal/inactivation. Neither the dosing of H_20_2 in the ozonation was included in the FTA. Moreover, it was decided that the aim of the study was to describe the plant as it works today, neither how the plant has worked nor how it will be changed in the future.

In this study two definitions were applied:

- The *critical event database* is a list of events that affect the processes at plant and it is constantly updated by the operators. The *critical event database* exist for all the years the plant has been in operation

- *Failure time* is the assumed time when there is an increased microbial risk caused by a process' decreased performance (due to different process errors/failures).

The meetings also contained discussions regarding other risk assessment methods of the plant. There were suggestions and ideas for further studies whereas pathogen measurements could play a more important role with a study of possible correlations between pathogen breakthroughs and process failure events in the NGWRP.

5.1.2 The structure of the fault tree

The overview of the structure for the fault tree is described in Appendix I and in more details in Appendices II, III and IV. It was important that the group defined the failure events in a similar way. The discussions were focused on one process at a time and as mentioned, it was overall an iterative process.

One example of a discussion that occurred was weather an AND- or an OR-gate should be applied for the monitoring. For example, in the ozonation fault tree (see Appendix II), an AND-gate for the monitoring process would mean that a failure would only occur if the monitoring shows too high residual of ozone, at the same time as there is a failure with the ozonation process. This alternative includes the fact that failures can be remedied as the process is monitored and the failures are identified. However, the reason for not using an AND-gate was because it was already taken into consideration in the critical event database, as the critical events in the database are the discovered failures. Therefore, an OR-gate was chosen which resulted in a higher probability of failure compared to an AND-gate. Consequently, the safe side approach was applied.

5.1.3 The critical event database used in the FTA

At NGWRP, there is a critical event database, where failure events that occur at the plant are listed. Some of the data for the fault tree model was brought out from the critical event database. As the plant is dealing with different challenges each year, the critical event database consequently changes. For instance, during the year of 2006 many difficulties were faced while the years 2009-2010 characterize the present conditions and situation at NGWRP. The later period exhibited fewer failures in total, but more problems with the power supply.

Finally the critical event data of the years 2009 and 2010 was used for all events. However for the UF and chlorination, data from the years 2006-2008 were also used as very few events happened in 2009-2010. In Appendices VI, VII and VIII the collected values for the critical events of ozonation, UF, chlorination and power failures are presented.

5.1.4 Estimations: length of failure times (for defining downtime) in the FTA

One major discussion at the workshop was regarding the critical event database and what failure time for the different processes should be applied in the analysis. The critical event database was considered to not be sufficient to use as source regarding the length of failure times. Instead estimations were needed for the failure time. There were at first two clearly different approaches of how to estimate the failure times which would have resulted in very different probability of failure. However, after discussions some compromises led to a decision regarding the failure times.

When identifying the failure times, an important part was recycling of not sufficient treated water as recycling leads to an immediate decrease of the risk. As described it is both performed after ozonation, after GAC and there is also a possibility to recycle the final water, even though it happens very rarely[9]. Furthermore, maintenance and other reconstruction work that were planned in advance were not considered as microbiological risks.

The final decisions of failure time were done based the following: For the ozonation, the water will only be delivered when residual ozone measurement shows values within process specification. However, it was considered being a risk if there is an insufficient contact time as it will reduce the CT value. Failure time for the main ozonation process was agreed after discussions. Furthermore stops of the plant and recycling are considered to be the same risk and therefore have similar failure times. Failure times of the chlorination and the UF is approximated based on the time it takes for the water to travel from the ozonation to the chlorination and the UF. The failure time estimations of the different processes are shown in Table 1 and in the FTA these were described as Gamma distributions.

Table 1 Failure times for different processes.

Type of failure	**Min** (5%-percentile)	**Max** (95%-percentile)
Ozonation[a]	5 minutes + time between failure and action is taking according to the critical event database	1 hour
UF	40 minutes	1 hour
Chlorination	60 minutes	2 hours

[a] An ozonation failure in the critical event database was not considered as a failure if the duration was longer than 12 hours.

[9] René Mertens Operator Manager WINGOC, personal communication May 2011.

Many of the failures originated from power supply failures and therefore a definition of different power failures was agreed on as presented below; the failure times is shown in Table 2. Power supply failures can be divided into two different types: power dips and power outage. All power failures are seen as uncontrolled events that sometimes lead to other process failures, even though that is not seen in the fault tree structure. Furthermore it was agreed that a power failure affect differently and may cause different problems.

Different kind of power failures:

- *Power dip*: the power goes off for about 1-3 seconds.
- *Power dip when no recycling or other action is taken:* It was difficult to determine whether this is a failure or not, as there is no proof that a failure is taking place as a consequence of the power dip. However agreements were based on the fact that it is a risk procedure.
- *Power dip and recycling is taking place*: It should be seen as a similar failure as power outage. It can for example cause instrument problems.
- *Power outage:* An uncontrolled event where the power is off for a period of different length.

As mentioned earlier, recycling is when treated water is considered insufficient treated and therefore stopped from continuing through the plant and re-introduced in the beginning of the treatment train.

Table 2 Definitions of different power failure times.

Description of failure	**Estimated failure time**
Power dip with recycling	• The recycling event was < 2 hours → the failure time was seen as the same as in the critical event database. • The recycling event was > 2 hours → the failure time was seen as an average of 2 hours.
Power dip when no action was taken	• The average risk was estimated to 1 hour
Power outage	• The plant stop was < 2 → the failure time was seen as the same as in the critical event database. • The plant stop was > 2 hours → the failure time was defined as 2 hours.

5.1.5 Numbers of failures (for defining uptime) in the FTA

Some of the expected failure events in the constructed fault trees were not found in the critical event database, and the possible reasons varied. Some failures had not happened during the chosen time period, others were not so clearly indicated in the critical event database. Hence, the numbers of failures needed to be estimated for these events. The sources of the estimations are presented in Appendix XI.

One example of an event that is based on estimation is monitoring of the different processes. That failure was not indicated in the critical event database, therefore number of failures were estimated, see Appendix XI.

The majority of the uptime data in the UF fault tree originate from estimations; this is due to the process type. As an example, the UF process consists of fibres that can break and consequently allow untreated water to pass. Fibre breakages cannot be seen in the critical event database, therefore estimations were performed. Furthermore, severe failures in the UF are not very likely to happen but difficult to detect.

For the entire UF fault tree, two experts performed estimations; these estimations were eventually very different and therefore modelled separately. Consequently, there were two results of the UF fault tree, but only one (the more conservative one) was presented in the overall result. In Appendix X a list of the different numbers from the estimations can be seen.

5.1.6 Events not considered in the calculation in the FTA

When the fault tree was constructed, the workgroup decided to see all base events in the fault tree as possible failures. However, not all of the events had occurred and could therefore not be found in the data base. Furthermore some of the estimations were not seen as feasible to use in the FTA. Even though some failure events had happened, the plant had either been re-constructed or changed in respect to operation routines and consequently the failure events were not considered as risks anymore. The intention was to find data to all identified events in the fault tree, due to problems described and other reasons data was not always found. However, even if data was not added to all events, the structure of the fault tree was decided to remain intact as an indication of a possible failure risk.

Considering for instance, the events coarse particle failure and chemical cleaning failure in the UF fault tree, the estimated failure time of these events was not comparable with the ones estimated for the other events. The reason was that the period estimated was only representing a time of a low risk, therefore these were not a part of the calculation. In Appendix IX a list is showed of the failure events that were included in the fault tree structure but not in the fault tree calculation (and events for which other special considerations were made).

5.1.7 Probability calculation in the FTA

The fault tree calculations are based on equations 3.2 and 3.3 and these are described in more detail in Chapter 3.2. However, to obtain the probability (P_F) the failure rate (λ) and the repair rate (μ) were calculated as described in Appendix XII. All the parameters were modelled with Gamma distributions and the calculations were performed with Monte Carlo (MC) simulations. The results of the simulations are presented in Appendix XIII. Eventually data for the failure events were put into the fault tree and the calculations were performed with the equations 3.2 and 3.3.

5.1.8 Evaluations of the FTA

To evaluate the result, a sensitivity analysis was performed which produced a list with rank correlation coefficients, see Appendix XVI.

For the probability of total hours of failure per year (the overall failure of the FTA), five trials were performed by a Monte Carlo simulation, for the first four simulations 10,000 iterations were used and for the fifth 100,000 iterations were used. Those five trials can be seen in Appendix XV, where a difference in the average are seen, trail 1 is the value used in this study.

5.2 Quantitative microbial risk assessment at NGWRP

This chapter presents how the QMRA was performed at NGWRP. For the QMRA modelling (theory explained in Chapter 4.3) a newly developed software tool for microbial risk assessment was used. The tool was developed with financial support from the Swedish Water Association (Svenskt Vatten Utveckling) and the software Analytica was used as the platform. The tool's default values of dose-response and water consumption was used in this study.

5.2.1 Raw water input data to the QMRA model

The concentrations of *Norovirus*, *Giardia* and *Cryptosporidium* in the raw water can be seen in Table 3, where some values are based on measurements and some are based on estimations (see Appendix XVII for details). The raw water is the effluent of Gammams Water Care Work (GWCW) which is a wastewater treatment plant, for details see Chapter 3.4.1. The pathogen concentrations in this study were presented as two different levels, illustrating a normal state of the raw water and a more extreme level, see Table 4. The *normal risk level* (*NR*) is expressed as the pathogen level when there is no epidemic among the population, or at the most 0.2% incidences of infection. The *enhanced risk level* (*ER*) was aiming to represent a scenario where 50% of the population are infected and may contribute to an increased level in the raw water. The raw water concentrations were presented as Gamma distributions in the QMRA model.

Table 3 Raw water concentrations for Norovirus, Giardia and Cryptosporidium used in the QMRA model of NGWRP (5%-, 50%, 95%-percentiles, and mean value).

	NOROVIRUS [genes/l]		**GIARDIA** [cysts/l]		**CRYPTOSPORIDIUM** [oocysts/l]	
	NR	ER	NR	ER	NR	ER
P05	0	0.003	0	701	0	972
P50	0.002	0.504	0.250	7334	0.100	2510
P95	0.340	85.0	2.00	86,300	3.00	26,000
Mean	0.286	71.5	0.506	24,200	0.551	7,120

Table 4 The two pathogen risk levels used in the study.

Pathogen level	*Description*
NR = Normal risk level	NR is a normal pathogen level in the raw water when there is no epidemic among the population, or at the most 0.2% incidences of infection.
ER = Enhanced risk level	ER is an enhanced pathogen level in the water, when 50% of the population is infected.

There were no concentrations of *Norovirus* were measured at the NGWRP. There have only been PCR measurements of enteric viruses carried out, which only shows if enteric viruses are present or not (presence/absence). These were not useable in this study because the concentration was needed. In addition, the PCR measurements at NGWRP that had been performed were under criticism[10].

The *Norovirus* concentrations were instead calculated based on estimations of the portion among the population that are infected. The pathogen content in the source (P_d) was calculated according to equation 4.1 (Åström 2011).

$$P_d = p \cdot \frac{P_f}{I_f} \cdot I_d \qquad (4.1)$$

In the equation, P_f equals the pathogen content in fresh faecal material and I_f is the indicator content in fresh faecal material and these values were found in literature, see Table 5. I_d equals the indicator content in the source were a mean value of *E. coli* in GWCW's effluent (measurements performed by Gammams laboratory at the City of Windhoek once a week in the time span of June 2005-October 2007) was applied in the calculation.

For the normal risk levels (NR) of *Norovirus* in the raw water, p was estimated to be 0.2% (p is the prevalence = portion of the population infected in a given moment). For the enhanced risk levels (ER), it was estimated that half of the population was infected (p=50%). Furthermore, it was assumed that 1 of 10,000 Norovirus genes are viable/infectious to individuals (Rigotto et al. 2011).

Cryptosporidium and *Giardia* concentrations were measured in GWCW's effluent once every week for GWCW's effluent in the period 1996–1999. The principal of the method was that 100 litres of sample was filtered, purified, stained and microscopically counted. The method could not distinguish between viable and non-viable cyst/oocysts. Throughout the measurement period there were 74 measurements performed, of which 58% and 34% were positive for *Giardia* and *Cryptosporidium* respectively (Menge et al. 2001).

[10] Jürgen Menge, laboratory chief at City of Windhoek, personal communication May 2011.

The *NR's* for *Giardia* and *Cryptosporidium* were expressed by these measurement values and the *ER's* were calculated with equation 4.1, in the same manner as the *Norovirus* levels were calculated.

Table 5 Data used in the calculations of pathogen concentrations in the raw water.

Parameter	*Value/Proportion*	*Reference*
Prevalens (*p*)	For NR, p = 0.2% For ER, p = 50%	
Norovirus content in faecal material (P_f)	Lognormal ($10^{5.30}$; $10^{7.08}$; $10^{9.46}$)[a]	Nordgren et al. (2009)
Cryptosporidium content in faecal material (P_f)	Normal ($10^{7.00}$; $10^{1.00}$)[a]	Girdwood and Smith (1999)
Giardia content in faecal material (P_f)	Up to 10^8 cysts/g, with this value a distribution was estimated: Triangle ($10^{3.00}$; $10^{6.00}$; $10^{8.00}$)[a]	Smittskyddsinstitutet (2011)
E. coli content in faecal material (I_f)	Triangle ($10^{5.30}$; $10^{6.80}$; $10^{8.88}$)[a]	Reischer et al. (2007)
E. coli concentration in GWCW's effluent (I_d)	787 cfu/100 ml (mean value)	

[a]The distributions are expressed as Lognormal (5%; 50%; 95%), Normal (mean; standard deviation) and Triangle (min, likeliest, max)

5.2.2 Process input data to the QMRA model

In the model, the removal or inactivation efficiency of pathogens was described as log removal/inactivation, see Table 7. As an example, 1 log removal/inactivation corresponds to 90% removal/inactivation of a specific pathogen (2 log removal/inactivation corresponds to 99%, 3 log removal/inactivation corresponds to 99.9% etc). For the QMRA modelling, two different operation modes were defined: o*ptimal operation* and *sub-optimal operation*.

- *Optimal operation* was defined as a process operation without any disturbances or failures.
- *Sub-optimal operation* was defined as a process operation when there is a failure in the process operation or some kind of disturbance of the process that decreases its performance.

The removal or inactivation efficiency of each process at NGWRP was identified with different methods.

Concerning *optimal operation* of the conventional treatment process, the log removal was calculated with measurement values of indicator organisms at the plant. Measurements of *Somatic coliphage* and *Clostridium viable* were used to calculate the removal of *Norovirus* and *Giardia*/*Cryptosporidium* respectively. The indicator organism concentration (IC) for the specific sample points were measured once every week throughout the period June 2005-October 2007 and the log removal was calculated, according to equation 4.2. This was performed for each individual measurement occasion and distributions of the log removals were structured.

$$\text{Log removal}_{\text{conventional treatment}} = \text{Log}_{\text{IC raw water}} - \text{Log}_{\text{IC after conventional treatment}} \quad (4.2)$$

This approach was partly used for the *optimal operation* of ozonation but could not be applied for the *optimal operation* of GAC, UF and chlorination because the measured levels of indicator organisms were approaching zero after the ozonation process.

For the disinfection processes, CT-values were calculated, see Table 6 (see Appendix XIX and XX for further details). With the CT-values, corresponding log inactivations, for *optimal operation*, were found in Ødegaard et al. (2009) and Smeets et al. (2006). When the log inactivation was larger than 10, it was estimated to 10 as maximum, which equals 99.99999999% inactivation and was considered as sufficient accurate.

Table 6 Calculated CT-values for the ozonation and the chlorination with corresponding log inactivation values.

Disinfection process	**CT-value (mg min/l)**	**Log inactivation**		
		Norovirus	*Giardia*	*Cryptosporidium*
Ozonation	15	54	25	1.2
Chlorination	27	13	0.62	0

For the GAC and the UF process, literature values were used for *optimal operation*. A report by Microrisk (Smeets et al. 2006) was applied as its data was based on several literature studies and considered reliable. The GAC process is, as mentioned, not considered as a barrier but makes a small difference in the pathogen removal and is therefore part of the QMRA model. The pathogen removal in the UF process is considered to include fibre breakages as a part of the normal operation.

The inactivation of *Cryptosporidium* (for *optimal operation*) in the ozonation was identified through measurements of indicator organisms, similar as described above for the conventional treatment. However, the calculations only included the occasions when there was a breakthrough of the indicator organism *Clostridium viable* (48% of the measured occasions). The mean value of these calculated log inactivations were correlating with the value indicated with CT-value calculation (see Table 6). Hence, the values were considered reasonable.

The sub-optimal values are based on estimations. The UF process was considered to be the most stable process that is not easily disturbed by failures. The conventional treatment and the GAC process were presumed to be more affected in *sub-optimal operation*. The disinfection processes were seen as the most sensitive processes, i.e. their inactivation efficiency in *sub-optimal operation* can easily be disturbed.

Compliance of the process data can be seen in Table 7 (for details see Appendix XVIII) where the log removal/inactivations for *optimal operation* are presented for each process. Moreover, the values for *sub-optimal operation* are showed within brackets.

5.2.3 Modelled scenarios in the QMRA model

With the raw water input data and the process input data, the QMRA model were created and different scenarios were modelled, see Table 8.

Scenario 1 aimed to show the optimal situation when there are no process failures and normal risk level of the raw water (*NR*).

Scenario 2 aimed to illustrate the situation when the raw water levels increase to an enhanced risk level (*ER*) where half of the population are assumed to be infected in 40 days in one year.

Scenario 3-6 were modelled to illustrate when each of the barriers individually are in *sub-optimal operation*. The failure time throughout a year from the FTA was incorporated.

The processes affect each other, which is not included in the model. In reality, a failure in one process most often affects the following processes[11]. Therefore, *scenario 7* was modelled to illustrate what the risk of infection would be caused when the conventional treatment is in *sub-optimal operation* and the ozonation, the GAC and the UF are therefore affected. The failure time throughout a year from the FTA was incorporated.

Scenario 8 involves every process' *sub-optimal operation* during the failure time throughout a year from the FTA. This means that all the *sub-optimal operations* of the processes are included one by one. This scenario is considered as the most realistic scenario as it is likely that sub-optimal operation of the different processes will occur.

The *scenario 9* was meant to show the possible effects of a countermeasure when adding a UV-light process with 2 parallel lines and 25 mJ/cm^2 (Lundberg Abrahamsson et al. 2009) into the treatment train.

The failure time throughout a year from the FTA (Table 9) was combined with the QMRA result (P_{daily}) and consequently P_{annual} was obtained with equation 3.4, see Appendix XIX. Furthermore, the theory can be seen in Chapter 3.3.

[11] Siegfried Mueller Process, Research and Technical Manager WINGOC, personal communication May 2011.

Table 7 *Process input data representing optimal operation at NGWRP (values within brackets represent sub-optimal operation).*

Conventional treatment [Log removal][a]			
	Norovirus	*Giardia*	*Cryptosporidium*
Min	**1.2** (0.23)	**1.7** (0.71)	**1.7** (0.71)
Mean	**2.2** (1.2)	**2.6** (1.6)	**2.6** (1.6)
Max	**3.8** (2.8)	**3.5** (2.5)	**3.5** (2.5)
Main ozonation [Log inactivation]			
Min	**8.0**[b] (0)	**8.0**[b] (0)	**0.31**[a] (0)
Mean	**9.5**[b] (2.5)	**9.5**[b] (2.5)	**1.2**[a] (0.50)
Max	**10**[b] (4.0)	**10**[b] (4.0)	**2.0**[a] (0.70)
Granular activated carbon [Log removal][c]			
Min	**0.2** (0.1)	**0.4** (0.2)	**0.7** (0.3)
Mean	**0.4** (0.2)	**1.7** (0.8)	**0.9** (0.4)
Max	**0.7** (0.6)	**3.3** (1.5)	**1.1** (0.9)
Ultra filtration [Log removal][c]			
Min	**6.0** (4.5)	**6.5** (5.0)	**6.5** (5.0)
Mean	**6.5** (5.0)	**7.0** (5.5)	**7.0** (5.5)
Max	**7.0** (6.0)	**7.5** (6.5)	**7.5** (6.5)
Chlorination [Log inactivation][b]			
Min	**8.0** (0)	**0.30** (0)	**0**
Mean	**9.5** (2.5)	**0.62** (0.10)	**0**
Max	**10** (4.0)	**0.90** (0.20)	**0**

a These process data were defined through calculations with indicator organisms, as described above.
b These process data were defined through a CT-value calculation, as described above.
c These process data were found in the literatures (Smeets et al. 2006) and (Ødegaard et al. 2009).

Table 8 The nine scenarios modelled in the QMRA model.

Scenario	**Raw water level**	**Process operation**				
		Conv. treat.	Ozon-ation	GAC	UF	Chlor-ination
1: Normal	NR	N	N	N	N	N
2: Epidemic 40 days	ER	N	N	N	N	N
3: Conventional treatment in sub-optimal operation	NR	S	N	N	N	N
4: Main ozonation in sub-optimal operation	NR	N	S	N	N	N
5: UF membrane process in sub-optimal operation	NR	N	N	N	S	N
6: Disinfection process in sub-optimal operation	NR	N	N	N	N	S
7: Conventional treatment in sub-optimal and following processes are being affected	NR	S	S	S	S-N	N
8: Realistic (All processes in sub-optimal mode separately)	NR	S	S	N	S	S
9: Adding UV	NR	N	N	N	N	N

NR = Normal risk level, ER = Enhanced risk level, N = Normal operation all the year; S = Sub-optimal operation during the failure time per year specified for the process in the FTA, the rest of the year normal operation is presumed; S-N = operation efficiency between normal and sub-optimal during the failure time per year specified for the process in the FTA, the rest of the year normal operation is presumed. S-N for UF = (Norovirus: 5.5, 6.0, 6.5) (Giardia: 6.0, 6.5, 7.0) (Cryptosporidium: 6.0, 6.5, 7.0) log removal.

6 Result

The result from the FTA and the QMRA is presented in this chapter and further details are described in the appendices as referenced in this chapter.

6.1 Fault tree analysis result

The results from the fault tree model are presented in Table 9 and it describes the mean time of failure per year that the process failures are likely to occur. The overall failure is defined as *microbiological quality failure* and is in total 134 hours per year. The *microbiological quality* failure is the combination of all the other failures listed in the table. In Table 9 it can be seen that ozonation, UF and chlorination have a failure time within the same range. However conventional treatment is slightly higher; as the failure time is a value used from the previous study. Furthermore the power contributes to about 42% of the total failure time for all the processes and can therefore be seen as a major risk.

Table 9 Hours of failure per year (mean value) for FTA.

Description of failure	***Hours of failure/ year mean value***
Microbiological quality failure (combination of all failures)	**134**
Main ozonation failure	19
UF failure	25
Chlorination failure	18
Power failure	55
Conventional treatment	37

In Table 10 the mean probability of failure (P_F) is presented, as well as the uptime ($1/\lambda$) and the downtime ($1/\mu$). Uptime is defined as the time of normal operation until failure occurs and is described in months. Downtime is the length of a process failure and is described in hours. Regarding downtime: conventional treatment has the longest mean downtime of 2.5 hours; chlorination has a downtime of 1.4 hour UF of 0.8 hour and ozonation the lowest of 0.4 hour. For the uptime: power failure occurred with a mean value every 6.5 days and main ozonation every 8.6 days, they happen more frequently than the other processes and consequently have the lowest uptime. In the calculation of the probability of failure (P_F) both μ and λ were taken into consideration. In Appendix XIV there is a more detailed description of uptime, downtime and probability of failure.

Table 10 Result of probability of failure, uptime and downtime (mean values).

Result with mean value	Micro-biological	Main ozonation	UF	Chlori-nation	Conv. treat.	Power supply
Probability of failure, P_F	0.0153	0.0021	0.0029	0.0021	0.0042	0.0063
Uptime (days), 1/λ	2.4	8.6	11.7	30.7	30.0	6.5
Downtime (hours), 1/μ	0.9	0.4	0.8	1.4	2.5	1.0

In Figure 14 the probability of failure (P_F) of the different processes can be seen. The microbiological failure is the sum of the different process failure times. The hours of failure per year for the total *microbiological quality* failure, seen in Table 9, is less than the exact sum of the process failure times one by one. The reason is that the combinations of failures are taken into consideration in the total *microbiological quality* failure, e.g. main ozonation failure can happen in the same time as UF failure. Moreover, the total *microbiological quality* failure involves all the other different failure distributions. Hence, it is likely that the mean values do not correlate.

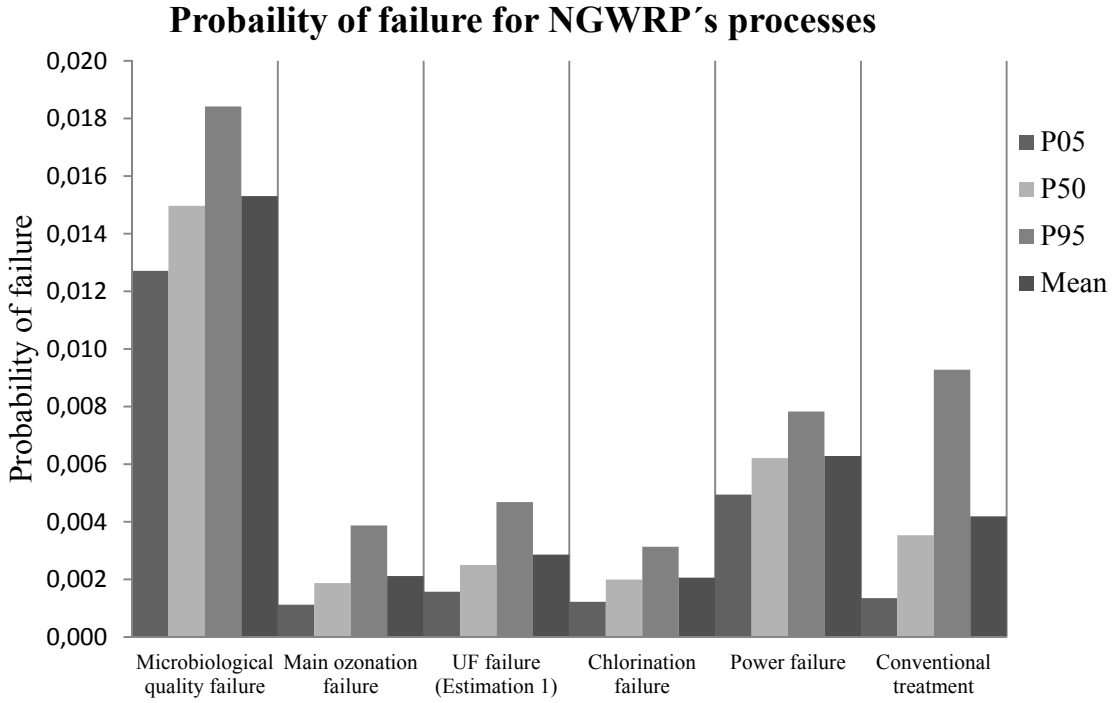

Figure 14 Probability of failure, from the FTA, of the different processes and power failure (presented with 5%, 50%, 95%-percentile values and mean value).

For the UF failure two estimations were performed (as described in method chapter 5.1.2) and the result from these estimations were 22 and 10 hours of failure per year. Estimation 1 of 22 hours of failure per year is the representing the most conservative value and the one considered in the result.

Table 11 describes the expected total failure time per year in seconds. It is a very low failure time of the three processes failing at the same while the failure time of two processes failing at the same time is higher. However all values for the total failure time per year are below 3.5 minutes per year. Power failure is not included in the combinations.

Table 11 Failure time in seconds per year for failures in several processes.

Combination of processes	**Total failure time (seconds) per year (mean value)**
Ozonation + UF	192
Ozonation + chlorination	138
Conv. treatment + Ozonation	281
UF + chlorination	187
Conv. treatment + UF	379
Conv. treatment + chlorine	273
Conv. treatment + Ozonation + UF	5.79
Conv. treatment + Ozonation + Chlorination	0.588
Conv. treatment + UF + Chlorination	0.780
Ozonation + UF + Chlorination	0.395
Failure of all processes	$5.94 \cdot 10^{-4}$

As described in Chapter 3.2.3 it is of great importance to evaluate the sensitivity and uncertainties of the input data. The result of the sensitivity analysis is showed in Figures 15, 16 and 17 and it is presented with rank correlation coefficients and it illustrate where the uncertainties in the final result originates from and what is the largest impact on the result. The sensitivity chart shows a large impact from the "air entrapment" (λ) for $1/\mu$ for microbiological quality failure which has a very high rank correlation coefficient. List of processes all rank correlation is seen in Appendix XVI.

In the Figures 15, 16 and 17 the "power dip" (λ and μ) and "power outage" (μ) originate from the power fault tree. The "back flushing failure" (λ and μ) and "air entrapment" (λ) originate from the UF fault tree. Finally, "air compressor" (λ and μ), "residual monitoring" (λ) and "ozone generator" (λ) originate from the ozonation fault tree.

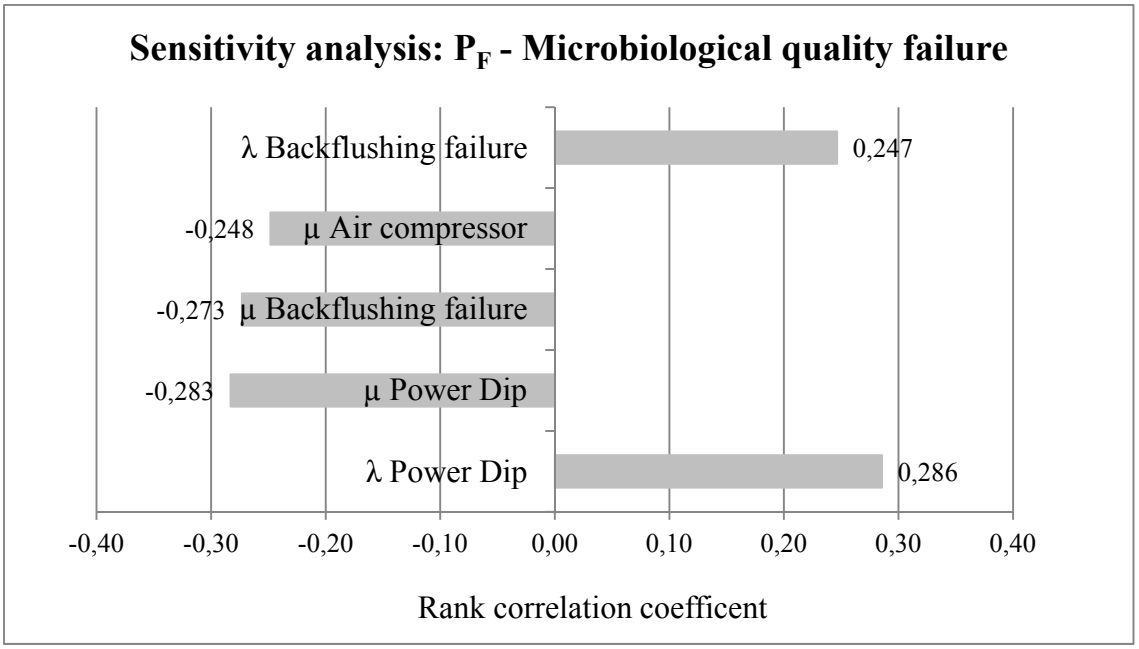

Figure 15 *Sensitivity analysis for the probability of microbiological failure in the fault tree.*

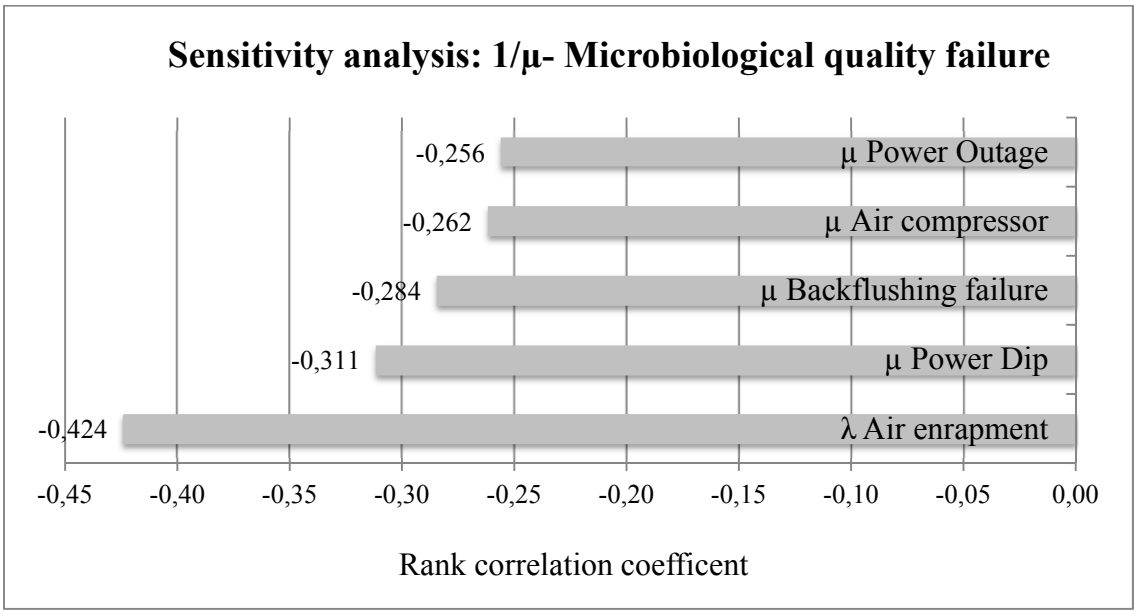

Figure 16 *Sensitivity analysis for the downtime of microbiological failure in the fault tree.*

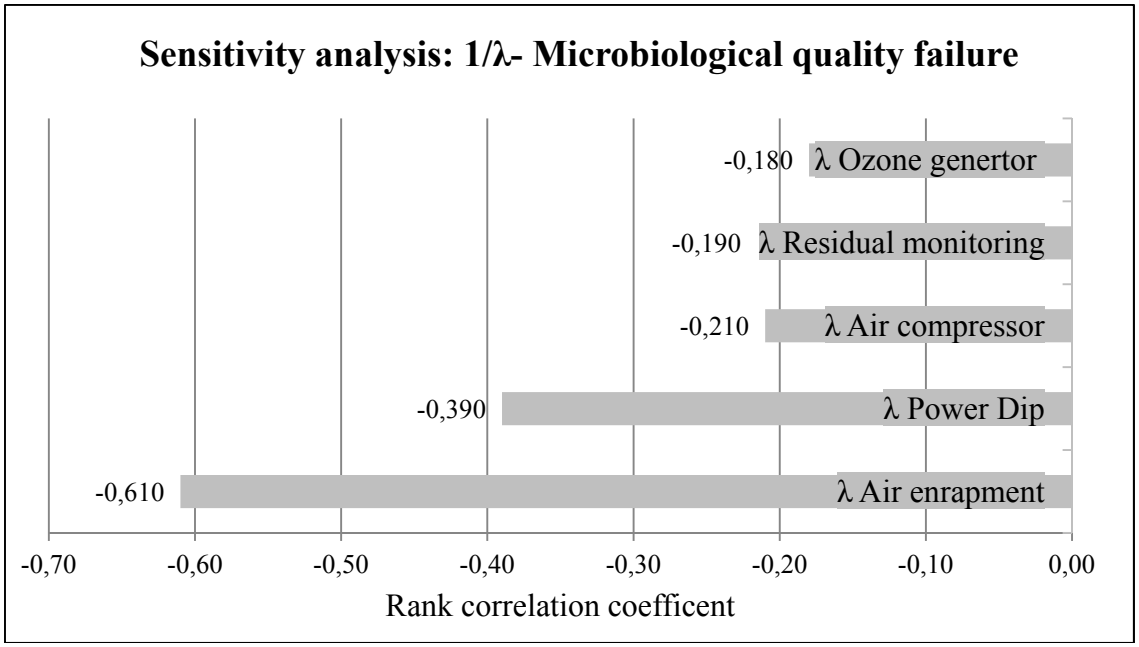

Figure 17 Sensitivity analysis for the uptime of microbiological failure in the fault tree.

6.2 QMRA result

The annual probabilities of infection (50%-percentile values) by *Norovirus*, *Giardia* and *Cryptosporidium* is presented in Figure 18 for nine scenarios modelled in this study. Moreover, the annual probability of infection by the three pathogens are presented in Figures 19, 20 and 21, with the 5%, 50%, 95%-percentile values. The health based target level, 10^{-4}, is marked with a red line. Furthermore, values that are 0 could not be showed in the diagrams because they are logarithmic (see Appendix XXI).

The scenarios modelled are seen below. There were normal risk levels of the raw water in all the scenarios except in scenario 2.

1) Optimal operation of the processes (#1).
2) Epidemic in 40 days with enhanced risk level in the raw water and optimal operation of the processes (#2).
3) Sub-optimal operation of conventional treatment (#3).
4) Sub-optimal operation of main ozonation (#4).
5) Sub-optimal operation of UF process (#5).
6) Sub-optimal operation of chlorination process (#6).
7) Sub-optimal operation of conventional treatment and the following processes are affected (#7).
8) Realistic (sub-optimal operation in all the processes with the duration specified in the FTA) (#8).
9) UV-light as an additional process with optimal operation of the other Processes (#9).

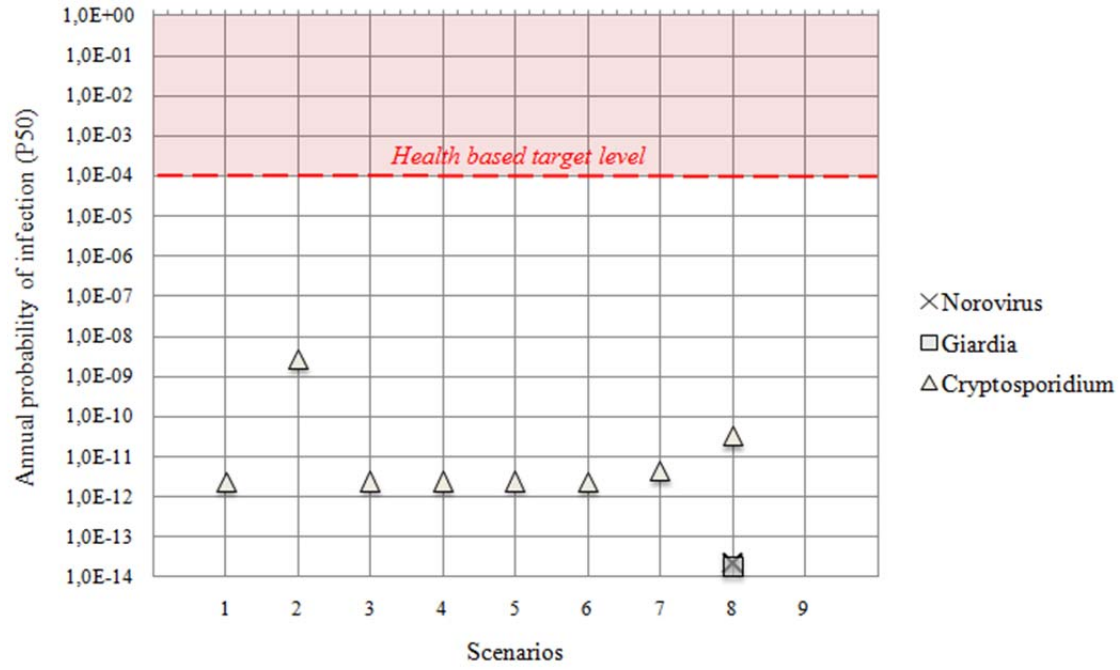

Figure 18 *Annual probability of infection (P50) by Norovirus, Giardia and Cryptosporidium.*

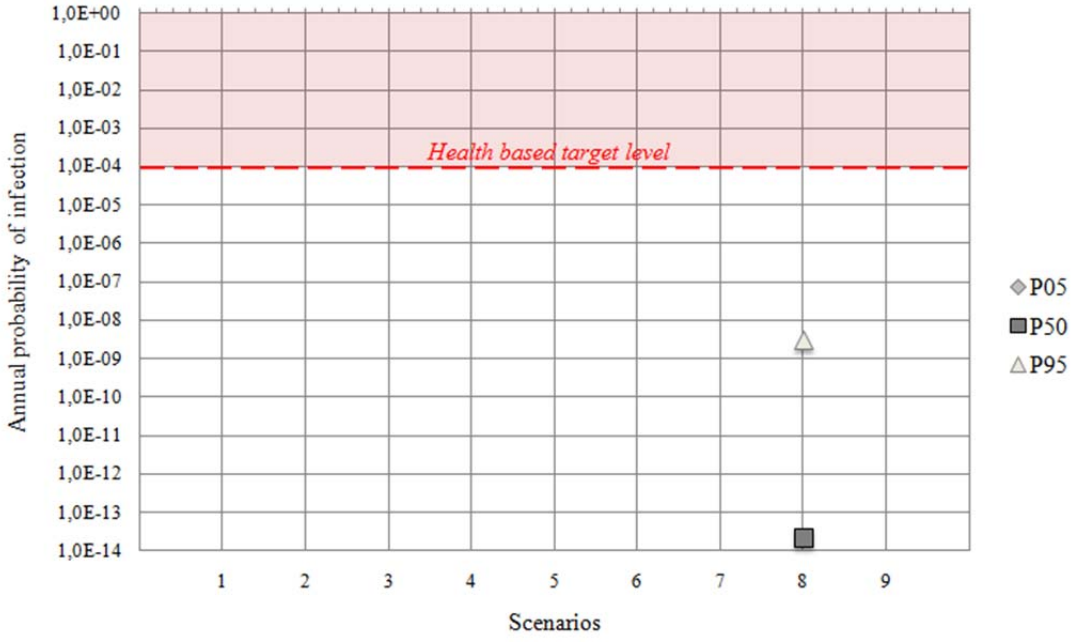

Figure 19 *Annual probability of infection by Norovirus.*

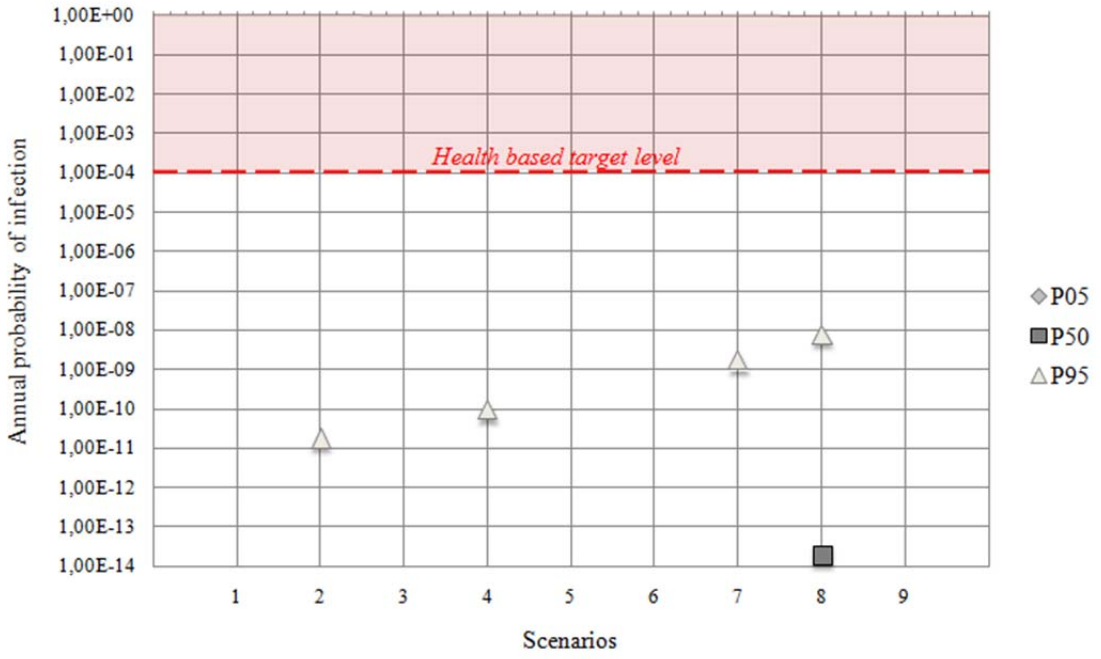

Figure 20 Annual probability of infection by Giardia.

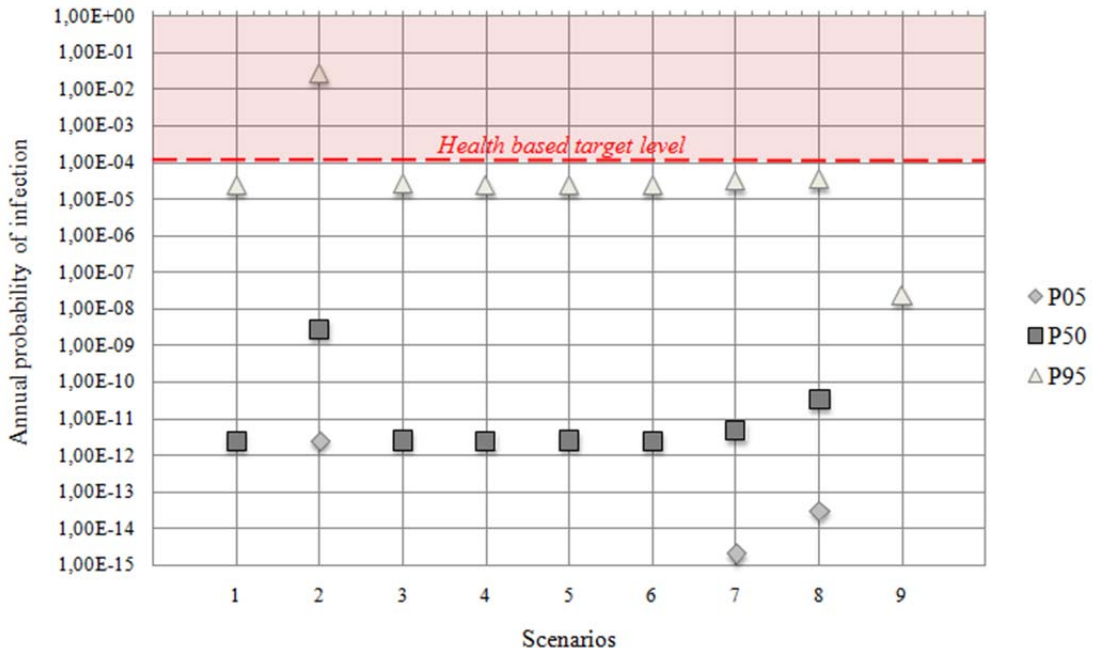

Figure 21 Annual probability of infection by Cryptosporidium.

The result shows that the risk of infection by *Norovirus* and *Giardia* is acceptable for all the modelled scenarios, for the 5%, 50% and the 95%-percentile values. The highest annual probability of infection by *Norovirus* is $2.3 \cdot 10^{-14}$ for the 95%-percentile in scenario 8. The corresponding highest annual probability of infection by *Giardia* is $2.0 \cdot 10^{-14}$ for the 95%-percentile in scenario 8. Both these values are far below the health based target of 10^{-4} annual probability of infection.

The 50%-percentile value of the annual probability of infection by *Cryptosporidium* is acceptable for all the nine scenarios, varying from 0 to 10^{-9}. Moreover, the 95%-percentile values, of scenario 1 and 3-9, have a probability of infection of about 10^{-5} which is an acceptable risk level but just below the health based target level. However, the annual probability of infection for scenario 2 is not acceptable for the 95%-percentile ($1.7 \cdot 10^{-4}$). In scenario 2, the epidemic period was defined as 40 days of infections among 50% of the population connected to the wastewater system. Still, the probability of infection is too high (for the 95%-percentile) already when the epidemic is lasting for only one day or longer. In Appendix XXI, daily probabilities of infection can be seen, where it is clear that UF is most important for *Cryptosporidium* removal.

7 Discussion

When evaluating the results, it is relevant to discuss the uncertainties and understand their impact on the result. This shows what is questionable in the result and what parts that could be further developed. Furthermore, the discussion handles the implications and what could be implemented as countermeasures to decrease the risk.

Aspects that affect the risk situation of the produced drinking water from NGWRP, except from the treatment processes, are for instance associated with the raw water and the distribution system. For example, when the raw water contains increased levels of algae and ammonium there is an increased risk, as it leads to difficulties for the treatment processes. These aspects are partly included in the FTA but not to a full extent. Furthermore, the risks in the distribution system are not included in the study, e.g. bio film in the pipes could decrease the quality of the drinking water before it reaches the consumers.

Moreover, the entire drinking water situation for the City of Windhoek has impacts on the risks at NGWRP. For example if the NGWRP must be shut down, other drinking water treatment plants in the city can provide the people with drinking water. On the other hand, in case of less rainfall than normal in Windhoek, there might be a stronger dependence on NGWRP. These circumstances need to be evaluated and taken into account to obtain an overall risk analysis for the drinking water situation in Windhoek.

7.1 Discussion of the Fault tree analysis

Throughout the fault tree analysis, uncertainties were indentified associated with the input data and the outcome from the workshops. In this chapter, these uncertainties are discussed and the results are evaluated.

7.1.1 Discussion of the workshop in the FTA

The experts in the workshop had different background, experience, knowledge and personalities. The study was influenced by this, for instance people emphasised different parts to be more important. Group members had different intensions and views of the study. When it comes to risk analysis, it is a sensitive subject and naturally you advocate for your own area. Still, the diversity of the group was considered as a great advantage for the outcome of the study.

The structure is very important for the result and the workshop members constructed the tree with their best knowledge. It should be mentioned that the construction of the tree was an iterative process where improvements were made throughout the workshop process to achieve a more accurate result. More discussions would have led to further improvements of the fault tree structure.

In the workshop there were two main discussions, firstly whether an AND- or an OR-gate should be applied in the top of the trees. The final decision to use an OR-gate ensured the result to be on the safe side. Secondly, there were discussions on how to estimate failure events for UF process. Eventually, there existed two different approaches of estimations, both were calculated and the most conservative opinion was chosen. The main reason for choosing an OR-gate and the most conservative UF estimation were to assure that the worst case was considered.

7.1.2 Discussion of the input data in the FTA

The data for the fault tree model was partly collected from the critical event database that describe the process failures at NGWRP. When the database was not used, expert estimations had to be performed.

In the critical event database, different time periods were used for the processes (as described in the method Chapter 5.1.3). Obviously, the years chosen affect the result and might lead to discontinuously.

Another difficulty, when using the critical event database, was that events defined in the fault tree model were not always possible to find, they might be too rare in such a limited period of time. In one way, events that happen most often are a larger risk to the plant. On the other hand, failure events that seldom occur or never have happened are often considered as a larger risk, partly as they are hard to predict in advance. One way to include these rare events would be to use database data over a longer period, for instance 10 years. However, there has been a continuously development and changes in the plant and the processes ten years ago are not always corresponding to the present treatment train. Generally, a FTA is often considered as a method that is efficient for finding rare events, however it was not always achieved to full extent in this study.

The data in the fault tree was not always described for the base events, instead found in a intermediate level of the tree, but it was not considered to affect the result. However, if the objective of using the fault tree would be to improve specific components of processes at the plant, it would be more favourable to have access to data of the failures more specific and not just as an overview.

The data used in the fault tree model was based on a mixture between the critical event database and expert judgements (estimations). For instance, the numbers of failures were often taken from the database but the length of the failures was mainly estimated by the experts in the workshop. It might be argued that it would have been preferable to instead use the same source to avoid mixture of data. On the other hand, it is a common approach and often considered necessary in risk analysis. However, the estimations were made because it seemed to be the most reasonable approach.

The critical event database is constantly updated by the operators at the plant, concerning the process failures. The descriptions of the critical events in the database are not always consequent, for instance the level of detail varies. Additionally, the critical event database was for this study interpreted by the authors to an applicable form that could be of practical use for the FTA. The uncertainties of the data from the database used in the FTA are affected both from how the database was formed and how it was interpreted.

7.1.3 Discussion of the FTA result

The result gives an indication of the risk, but no exact numbers. The highest probability of failure is represented by the power supply failure. Furthermore, when there is power supply failure, the processes' stability is disturbed and it might take time before normal operation is reached again. The highest probability of failure among the processes was represented by the conventional treatment. This seems reasonable since it consists of three very different parts that all needs to function.

Moreover, the ozonation-, UF- and chlorination processes have similar failure hours per year, even though ozonation failure happens more frequently. The duration of the failure was considered longer for UF and the chlorination compared to the ozonation. The failure time affect the result heavily and is considered as a major uncertainty for the FTA result. From the critical vent database and experienced by the personnel at NGWRP, there are clearly more often failures in the ozonation compared to the other processes. Even though the probability of failure in the ozonation is in the same order as for UF and chlorination, the failure for ozonation is considered as the highest, as it happens more frequently.

The fault tree of the conventional treatment process was created in a previous research project and was added to a complete fault tree created in this study. It should be stated that the data and the structure of the fault tree of the conventional treatment process had many differences to the ones created in this study. Therefore, it was not obvious how the result of the conventional treatment process can be compared with the other process results.

The sensitivity analysis shows how much each parameter contributed to the uncertainty of the result, with respect to how uncertain the parameter is and how it is included in the calculations. The results indicate that the failure of "power dip", "air entrapment" (UF fault tree) and "air compressor" (ozonation fault tree) had the largest impact on the main result of microbiological quality failure at NGWRP. If the FTA model of NGWRP would be further developed, the parameters with the largest uncertainty should then be prioritized to be investigated into more detail, as better input data decreases the uncertainties of the model and consequently provide a more accurate result.

The power failure was defined, as a top event rather than a base event. This was to assure that power failure was not included more than once in the fault tree. It also shows the complexity of the power supply as it affects the whole treatment process train, even though some parts of the plant is more directly influenced than others. A general problem with the power supply is the high likelihood to trigger other failures in the processes. Power failure is something out of control and it cannot be foreseen by managers or operators.

Chlorination is the final treatment process and therefore it could be considered sensitive due to the fact that there is a higher probability that the water will be delivered if the failure is not noticed. No other treatment process can correct what goes wrong here. Also the raw water and its quality is a major issue for the performance of the chlorination process. Moreover when the water leaves the NGWRP it is transported through pumping stations and reservoirs before it reaches the consumers. At some of the reservoirs and pump stations, additional chlorine is added which is not taken into consideration in this study.

It is of great importance to remember that Namibia is a developing country with limited resources. Therefore improving the electrical supply is a challenge for the country itself. However something to consider and evaluate is if there is a possibility and necessity for NGWRP to have a local power solution for the entire plant to avoid power dips or maybe even power outage for a limited period of time.

7.2 Discussion of Quantitative microbial risk assessment

In the Quantitative microbial risk assessment, uncertainties were identified associated with the raw water and the process input data (especially for sub-optimal operation). These are discussed in this chapter as well as an evaluation of the result. To perform a QMRA input data is needed and therefore this study was about making the most reasonable choice.

7.2.1 Discussion of the raw water input data in the QMRA

Norovirus levels in the raw water were calculated mainly based on estimations. Still a part in the calculation was the measurements of *E. coli* in the raw water. It might be stressed that *E. coli* is an indicator organism that is questionable. Therefore it would be an improvement for the study to measure actual *Norovirus* levels. However raw water values for *Giardia* and *Cryptosporidium* were based on measurements that took place in the 1990's. The city has changed since then, for example with more inhabitants and changed life styles. It would therefore be an advantage to measure the actual levels of *Giardia* and *Cryptosporidium* in the raw water. Also as the risk of infection by *Cryptosporidium* was found to be the highest it would be of special importance to measure *Cryptosporidium* levels in the raw water as well as throughout the treatment plant.

It is not obvious if historical measurement values as performed for *Giardia* and *Cryptosporidium* are better than estimations as mainly performed for *Norovirus*. One uncertainty is that measurements of pathogen levels often cover normal levels as well as increased levels (e.g. the case when there is an epidemic). Therefore, a simplification in this study was that the pathogen measurements were assumed to represent the normal levels with no epidemics.

Scenario 2 is an epidemic outbreak where the pathogen concentration is elevated. An exact percentage of people being infected and for what time period is of course difficult to determine, values used in this study can therefore be questioned.

There are certain issues with the raw water that is not taken into consideration in the QMRA. One aspect is that the only raw water source at NGWRP is treated sewage from GWCW as the quality of the Goreangab dam (previously also a raw water source) is too low. This is vulnerability for the NGWRP as it would be an advantage to have more than one raw water source. However it might be possible in the future to use the dam as a raw water source if the quality would be improved. Additionally, as the raw water is originating from treated sewage, it would be particularly sensitive if an epidemic would occur in the city. Many infected people increase the pathogen concentration in the raw water, and problems would occur if the treatment plant would not be able to handle the higher pathogen concentrations. This can be seen as the worst and most severe situation.

For this reason, it is obvious that GWCW, the wastewater treatment plant, is very important for the raw water quality, even though it is not included in this study. The WWTP are planned to be upgraded which will be an advantage for NGWRP. Finally an advantage for NGWRP is the preparedness of the difficult raw water, because it is always expected that the raw water contain high microbiological contamination.

7.2.2 Discussion of the process input data used in the QMRA

The process data used in the QMRA was obtained with different methods. The log removal data for conventional treatment for optimal operation were assumed reliable, as these were obtained from measurements of indicator organisms, achieved by a rigorous test program performed over a long period. However, the properties of the indicator organisms differ from the investigated pathogens. Still, the use of indicator organisms for removal and inactivation of pathogens is often considered as sufficient to use, as discussed in Chapter 2.5.4. The process data for ozonation, GAC, UF and chlorination (for optimal operation) were not based on indicator measurements, instead different methods were applied (see Chapter 4.2 for details). As an overall comment the most conservative values was believed to be used. Most uncertain were the process data for the sub-optimal operation of the processes, because they were based on estimations.

There were different approaches to identify log inactivations for the disinfection processes. Regarding ozonation, two main options were considered and the one chosen had input data that seemed reasonable. Also, it provided the most conservative approach. Concerning chlorination, there were two options available and the alternative that was less conservative was selected as it was based on a calculation performed with reasonable input data.

It was decided that the highest value of log removal/inactivation should not exceed 10 log units (i.e. ≤99.99999999% removal) for the processes because higher values did not seem reasonable and it might be questioned if an inactivation to that extent is possible. However, the choice of using a pre defined top value assured the safe side approach.

7.2.3 Discussion of the QMRA result

As a whole, NGWRP has good treatment efficiency according to the QMRA result which can be seen in the optimal scenario (#1). The probability of infection for the three pathogens investigated were acceptable and below the health based target level of 10^{-4}.

The probabilities of infection by *Norovirus* and *Giardia* were low for all modelled scenarios. Concerning *Norovirus*, the result indicated that, there is an increased risk with the realistic scenario (#8), but still far below the target level. When it comes to risk of infection by *Giardia*, there is a noticeable increase for some of the scenarios (#2, #4, #7 and #8), but the risks are still acceptable. Regarding identification of a critical process for the removal of pathogens, it is not possible to draw any conclusion for *Norovirus*. For *Giardia*, scenario 4 indicates that the ozonation process is the most important and can be considered as a critical process (see Appendix XXI).

The risk by *Cryptosporidium* is the most critical of the three pathogens investigated. The probability of infection is too high for the epidemic scenario (#2) for the 95%-percentile. This is the only case when the risk of infection is not tolerable. Furthermore the risk levels for scenarios 1 and 3-8 are acceptable for the 95%-percentile but near the health based target level. The best result for *Cryptosporidium* is showed when an UV light process is added (#9). The result also indicates that UF is an important process for the removal of *Cryptosporidium*, especially since a high portion of the pathogen removal is due to the UF.

In scenario 7 where the treatment processes affect one another, an increased risk of infection by *Giardia* can be seen, but it is within the accepted risk level. The scenario 8 can be seen as the most likely scenario because it includes all calculated failure time in sub-optimal operation. This scenario indicates that the risk of infection by *Norovirus* and *Giardia* is increased but beneath the acceptable level. With *Cryptosporidium*, an increased risk compared to the normal scenario (#1) can be seen but the change is similar to other scenarios.

The FTA result was incorporated in the calculation of the QMRA result (see equation 3.4) and there are advantages when these methods are combined. The main reason is that the study reaches closer the actual situation at the plant and it was possible to use more realistic failure times than estimations. Moreover, the FTA result in itself can be very hard to interpret into something applicable but the combination with QMRA shows the consequences for the consumers of process failures. On the other hand, there are limitations when combining these methods. For instance the process failure times obtained with the FTA are small, therefore the probability of infection for sub-optimal operation of the different processes are very similar and hard to compare.

The program tool used in the QMRA modelling showed some unexpected outcomes for the mean value. The mean value was often approaching the 95%-percentile, with respect to the used input data distributions. This was possibly related to problems within the program tool itself, associated with the pre-defined processes "conventional treatment" and "Slow Sand Filtration/Biological Filtration Performance". Furthermore, the type of distributions chosen for the raw water possibly had an impact and led to an unreasonable high mean value.

To take this study further or to improve the QMRA, it would be interesting to measure the actual levels of *Cryptosporidium* in the raw water because it is part of the most severe result. The *Norovirus* levels used in the QMRA-model involve uncertainties but it would only be advantageous to measure the actual levels if it is possible to measure the viable genes only. To improve the process data, it would be good to measure site specific removal of the different pathogens. Additionally, the study would be enlarged if other pathogens would be modelled, for instance Salmonella or Rotavirus.

To improve the situation at NGWRP, it would be suitable to increase the inactivation of *Cryptosporidium*. This could be achieved if UV light would be introduced into the treatment train, and as can be seen in scenario 9, the probability of infection by *Cryptosporidium* was clearly decreased when UV light was added. Another possibility would be to introduce reverse osmosis (RO) as it is already being considered at NGWRP[12], due to problem with too high salt concentration in the final water. RO has similar difficulties and risks as UF but in RO operation there is also a higher pressure difference which leads to a higher risk of break through[13]. However RO might have an advantage as there is a possibility of more online monitoring. Furthermore combining RO and UF would also be a possibility as it decreases the risk even more.

[12] Jürgen Menge, laboratory chief at City of Windhoek, personal communication May 2011.

[13] Olof Bergstedt adjuncted Prof Göteborg Vatten, personal communication August 2011.

Finally, a combination of RO and UV light would be the alternative with the most decrease of the risk. Still, the financial aspect in comparison with the benefits is also important to consider.

8 Conclusions

The result from the Fault tree analysis (FTA) showed that power failure is the major issue. ultra filtration, ozonation and chlorination had similar failures times during a year, but ozonation was considered more severe as it occurred more frequently. The main uncertainties of the FTA result were associated with the input data and the outcome of the workshop.

The result of the Quantitative microbial risk assessment (QMRA) indicated that the probabilities of infection by *Norovirus* and *Giardia* were acceptable. However, the risk of infection by *Cryptosporidium* was not acceptable for the 95%-percentile value of the scenario with epidemic raw water levels. The uncertainties that mainly affected this result were the raw water input data and the process input data for sub-optimal operation.

In order to decrease the risks identified at NGWRP in this study, the suggestion was to evaluate an improved local power supply at the plant and to develop the ozonation process to decrease the failure rate. To decrease the risk of infection by *Cryptosporidium*, the result indicated that UV light would be an efficient countermeasure.

If this study should be taken further, regarding the FTA, it could be interesting to find more data about rare events. To improve the QMRA, it was suggested to measure the levels of *Cryptosporidium* as it showed the most critical result. To improve the process data, it would be favourable to measure site specific removal efficiency of the different pathogens.

Furthermore, the study can be enlarged by considering other pathogens than the three studied in this Master thesis', for instance *Salmonella* or *Rotavirus*. Also, a risk assessment could be stretched to involve long term aspects and other than microbiological risks, for instance chemical compounds. Additionally, improvements of the risk assessment could include e.g. the raw water, the distribution system and other drinking water treatment plants in Windhoek.

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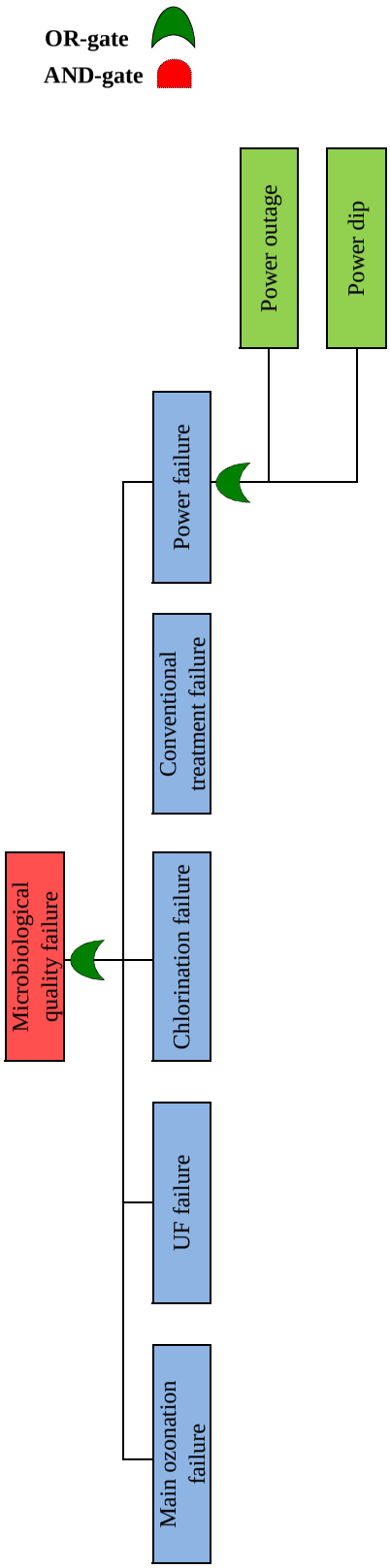
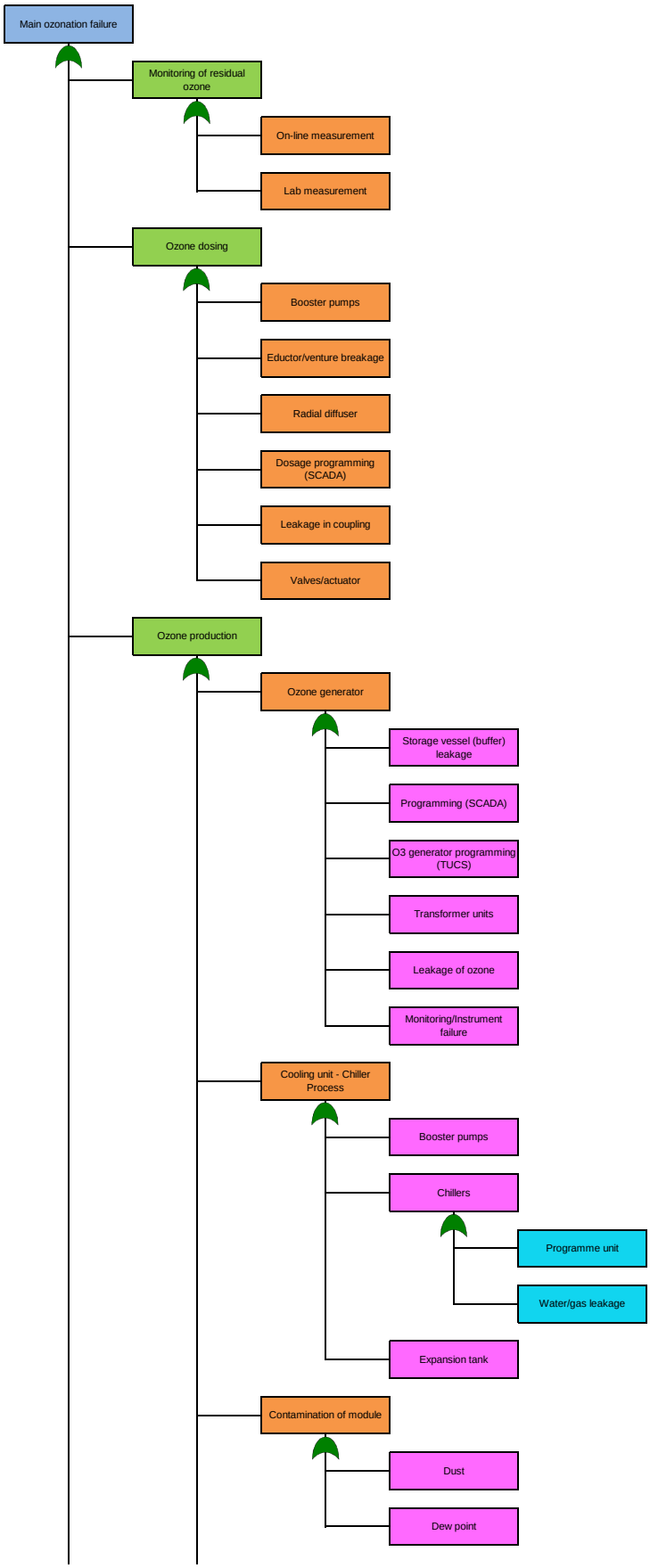
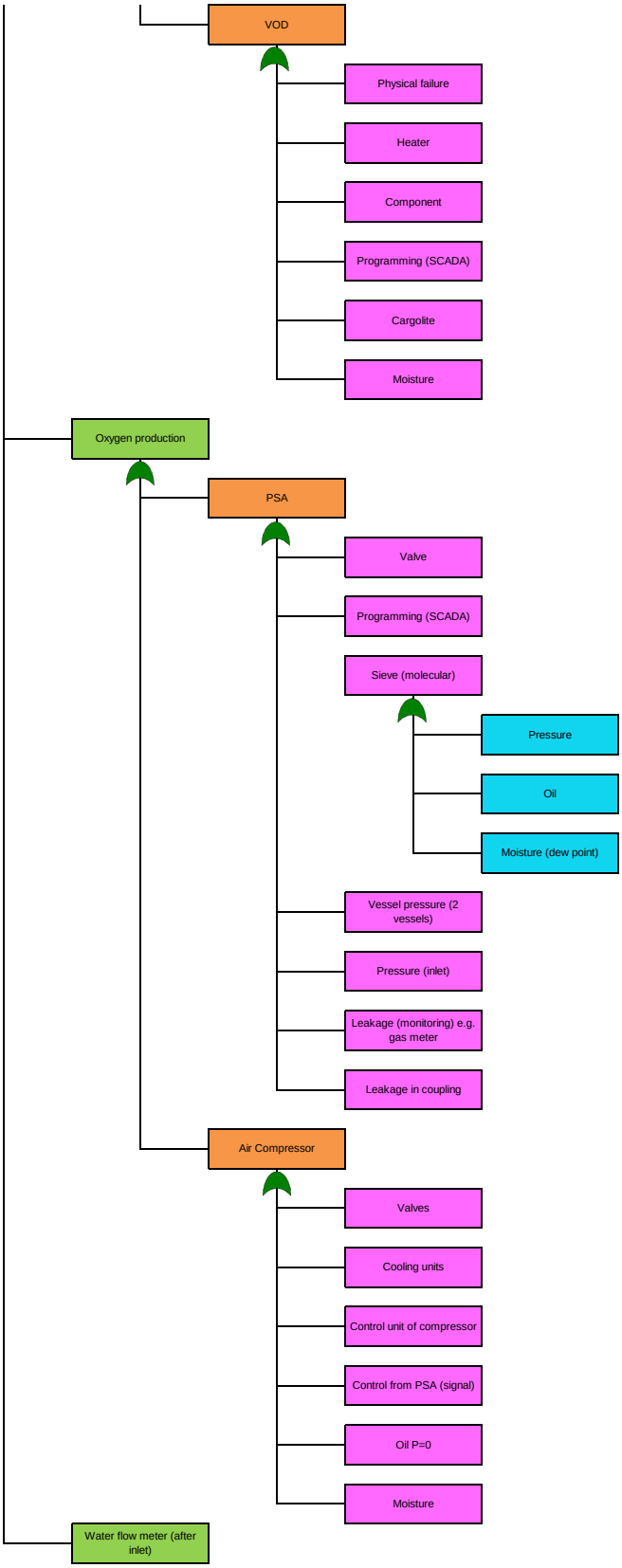
Appendix 1: Main fault tree

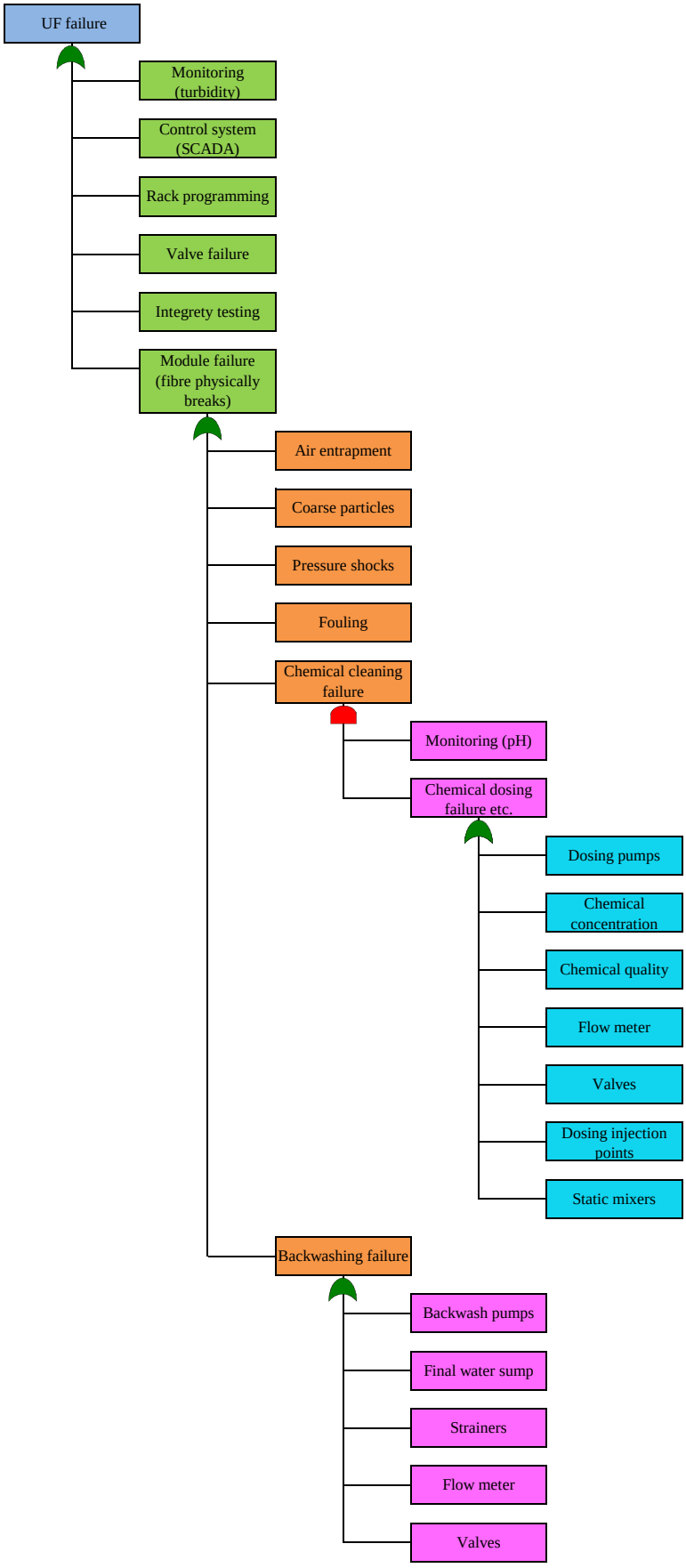


Appendix II: Main ozonation fault tree

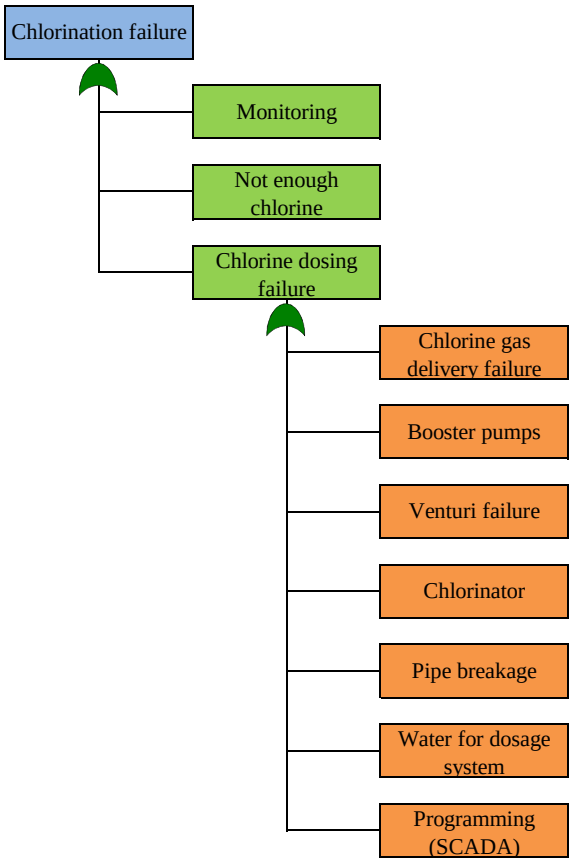



VOD
Physical failure
Heater
Component
Programming (SCADA)
Cargolite
Moisture
Oxygen production
PSA
Valve
Programming (SCADA)
Sieve (molecular)
Pressure
Oil
Moisture (dew point)
Vessel pressure (2 vessels)
Pressure (inlet)
Leakage (monitoring) e.g. gas meter
Leakage in coupling
Air Compressor
Valves
Cooling units
Control unit of compressor
Control from PSA (signal)
Oil P=0
Moisture
Water flow meter (after inlet)

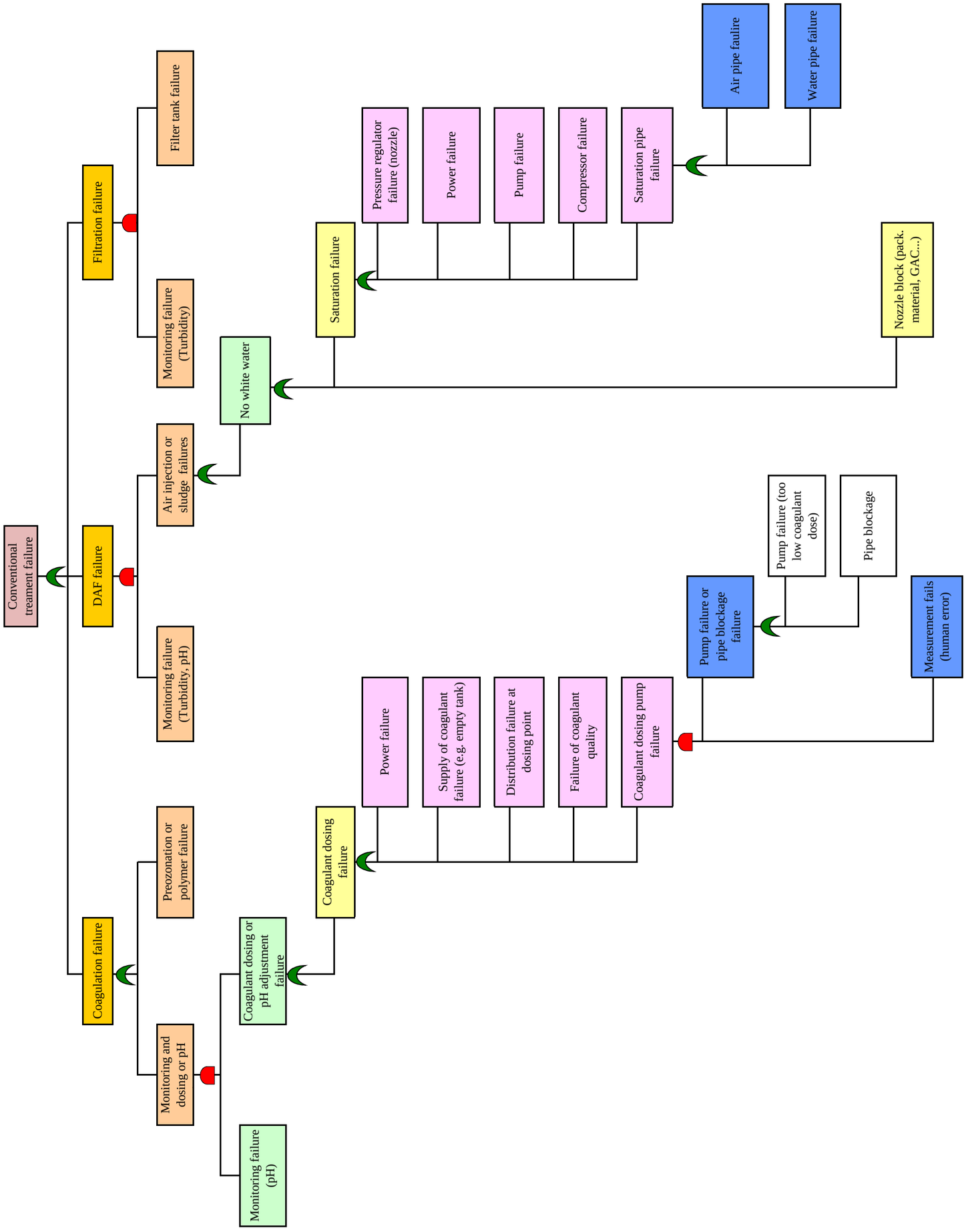
Appendix III: Ultra filtration fault tree



Appendix IV: Chlorination fault tree



Appendix V: Conventional treatment fault tree



Appendix VI: Ozonation failure data from the critical event database

2010-Ozontion failure			
Description of failure (as described in the critical event database)	**Numbers of failures**	**Time [hours] it was off**	**"The time between failure is discovered and action is taken"**
The plant is closed due to air compressor	7	5.55	03:07
Description of failure types to air compressor			
Started recycled due to Air compressor A tripped	1	1.58	00:00
Ozone Generators all stopped due to Air pressure had low oxygen	1	0.70	00:07
Air compressor A tripped .Ozone Gens Stopped	4	2.95	00:14
Regulated air pressure dropped	1	0.32	00:00
The plant is closed due to PSA	3	1.95	00:09
Description of failure types to PSA			
PSA Skid C Tripped on Low pressure	1	1.05	00:07
Start/Stop recycle-O3 gen stop due to low O2 pressure	1	0.77	00:00
PSA skid C fall off-Ozone Gens Fall off -Low pressure Switch	1	0.13	00:02
The plant is closed due to ozone generator	6	18.12	01:29
Description of failure types to ozone generator			
Start recycling due to ozone generators stopped at high temp	1	3.42	01:12
Due to low oxygen flow Ozone generators fall off	1	6.00	00:05
Start/Stop Recycling -03 Gens tripped due to low Pressure	1	0.15	00:00
Ozone Generators tripped due to low oxygen pressure	1	0.45	00:06
Start/Stop recycling due to low O2 pressure.	1	3.40	00:00
Stop plant-Main o3 pump A faulty	1	4.70	00:06
Total time 2010 the plant was closed due to ozone failure [hour]	**16**	**25.62**	**04:45**

It is recycled due to air compressors	*3*	*1.48*	*01:07*
Description of failure types			
Air compressor C tripped-Ozone Generator Falls Off.	2	0.98	00:13
Air Compressor C tripped	1	0.50	00:54
It is recycled due to PSA	3	2.53	00:38
Description of failure types to PSA			
PSA COMPRESSOR C tripped	1	1.07	00:10
Ozone generators tripped due to low O2 pressure/ PSA C tripped	1	1.45	00:28
recycling due PSA compressors tripped (due to power failure)	1	0.02	00:00
It is recykeld due to chillerplant	1	0.17	00:00
Description of failure types			

Start recycling/chiller plant tripped-Ozone generator tripped	1	0.17	00:00
It is recycled due to ozone generator	9	2.92	00:27
Description of failure type to ozone generator			
Started /Stopped Recycling due to switch at O3 GENS	1	0.78	00:00
Oxygen concentration low/ tripped ozone generators	1	0.17	00:14
Ozone Generators tripped due to low oxygen pressure	3	0.42	00:11
O3 Generator tripped-O2 KPA low	2	0.42	0
Ozone Generator A tripped on MCC mode.	1	0.37	00:00
Stopped/Start Recycling due to Ozone generator pressure dropped	1	0.77	00:00
Total time 2010 the plant is recycled due to ozone failure [hour]	**16**	**7.10**	**02:12**

2009-Ozonation failure			
Description of failure (as described in the critical event logg)	**Numbers of failures**	**time [hours] it was off**	**"The time bewtween failure discovered and action is taken"**
The plant is closed due to air compressor	8	7.32	00:02
Description of failure types			
PSA Plant tripped due to low O2 pressuer low oxygen pressure	7	3	00:02
Air compressor B tripped and O3 Gens stopped	1	2.32	00:00
It is closed due to PSA	1	0.77	01:05
Description of failure types			
PSA B and O3 Generators tripped	1	0.13	00:00
Blue pipe for Liquid trap at PSA plant burst	1	0.63	01:05
It is closed due to the chillerplant	3	2.93	00:00
Description of failure types			
Stop the plant. chiller fail to start	1	1.67	00:00
Start/stop recycle due to chiller plant outage	1	0.88	00:00
Start / Stopped recycling to restored temperature at chiller	1	0.38	00:00
The plant is closed due to ozone generator	2	6.00	00:15
Description of failure types to ozone generator			
Stop generator B – faulty	1	6.00	00:15
O3 generators stopped -low pressure	1	0.00	00:00
Total time 2009 the plant is closed due to ozone failure [hour]	**14**	**17.02**	**01:22**
It is recykeld due to air compressors	9	4.00	00:26
Description of failure types air compressors			
Oxygen Pressure dropped due to air compressor trip	1	1.43	00:14
PSA Plant tripped due to low O2 pressuer low oxygen pressure	5	1	00:03
Start/stopped recyclind due to Air compressor and PSA plant	1	0.00	00:00

Air compressor B and PSA B tripped due low Pressure.	1	0.42	00:05
Air compressor B tripped in MCC	1	0.33	00:04
It is recycled due to PSA		1.28	00:24
Description of failure types to PSA			
PSA Plant tripped	1	0.08	00:02
PSA Plant tripped due to low O2 pressuer low oxygen pressure	2	0.32	00:20
PSA compressor trip	1	0.88	00:02
PSA Air drier B tripped and find water leak inside and burning	1	0.00	00:00
It is recykeld due to chillerplant	4	4.27	00:01
Description of failure types			
Chiller plant trip .O3 Generators trip.	2	0.10	00:00
03 Gen A.Chiller C tripped-High temp	1	0.17	00:01
chiller plant C tripped (low temperature)(H: due to broken pipe line)	1	4.00	00:00
It is recykeld due to ozone generator	4	17.90	00:05
Description of failure types for the generator			
O2 pressure low & O3 Gens stopped.Recycled	1	0.68	00:00
Started / Stopped Recycled due to Ozone generators	1	17.00	00:00
Ozone generator tripped	1	0.18	00:00
Ozone generators stopped due to low oxygen pressure.	1	0.03	00:05
Total time 2009 the plant is recycled due to ozonation failure [hour]		**27.45**	**00:56**

Overview of values for ozonation fault tree used in the calculation	**Total number of failures**	**Number of events longer than 5 minutes**	**Average time of those events [min]**	**Max failure [min]**	**Min failure [min]**
Air compressor	28	3	00:25	60	6.45
PSA	13	3	00:27	60	8.19
Chillerplant	8			60	5.00
Ozone generator	21	5	00:22	60	9.05

Description of failure from estimations	**Time**	**Total number of failures**	**Average time**
Ozone dosing	216	5	300
VOD	120	1	10
Water flow meter	-	-	-

Appendix VII: Power failure from the critical event database

2009 – 2010

Power failure	Period measured [months]	Number of failures	Duration of failure [hours, sum of all events]
Power Dip - (Recycling or no action)	24	95	0.5
Power Outage - All areas - Stopped the plant	24	14	1.65

Appendix VIII: Ultra filtration and chlorination failure from the critical event database

UF 2006-2010 (membranes changed 2008)	Number of failures	Min failure time [min]	Max failure time [min]
All UF Racks tripped fail to start . RACK failure	1	40	60
Stopped plant due to faulty Norit/Membrane PLC	lasted too long-not consider a risk		
Stopped train 2 due to maintenance on membrane plant.	No failure		
Main Scada 1&2 and Norit Scada faulty.	1	40	60
Norit Scada outage - Monitor membrane plant manually.	1	40	60
Performed 5 Backflushes on UF Racks B+D and checked	No failure		
Membrane Plant Scada fail - Start recycling. 17:30	1	40	60
Reduce production rate to 750m3/h- low UF permeabilities. (fouling)	1	40	60
Membrane racks started to trip due to low air pressuer from small compressors. (valve)	1	40	60
Norit Scada & PLC failure.	1	40	60
Permeabilities of UF Racks Low falling under 200 ImhB. (fouling)	1	40	60
Deactivated UF Rack A for Integrity Test	No failure		
Experience problem with Norit scada	1	40	60
Membrane feed sump overflows	No failure		
Deactivate Uf Rack A for Integrity test	No failure		
Started / Stopped recycling.due to membranes not performing backflush	1	40	60
Membrane control centre fail/ freezed	1	40	60
Membrane plant control system freeze	lasted too long-not consider a risk		
Stopped/Start Recycling Reload UF Programme from main PLC	1	40	60
Number of failures totally for UF 2006-2010:	**12**		

Chlorination 2006 – 2010			
Chloor leakage in Cl2 room.	1	60	120
Recycled due to low chlorine at final water	1	60	120
Internal recycling due to broken chlorine pipe.	1	60	120
Start recycling due to low chlorone in final water/ NH3 detected	1	60	120
Reduce production rate /h due to low chlorine in water	1	60	120
Numbers of failures for chlorination 2006-2010	**5**		

Appendix IX: Considerations in the fault tree calculation

	These were specially considered in the calculation	
Ozonation	Contamination of module	Not considered as a failure due to reconstruction of the plant moreover it is also a failure that is hard to know if it cause the failure.
	Vent ozone destructor (VOD)	It is not a risk for the treatment of water. However. it may lead to a stop of the process and eventually it was included in the study (1 every 10th year) .
	Water flow meter (after inlet)	Not defined in the calculation as it is a low risk, furthermore it shouldn´t cause much problem if it happens. Therefore not included in the calculation.
UF	Coarse particle	Estimated as an increased risk for 1 week every second year. However it was not considered in the calculation as the time is only when there is an increased risk for a failure.
	Chemical cleaning	Estimated as an increased risk for 1 week every third month. However it was not considered as a failure time as the time is only when there is an increased risk for a failure. Eventually not consider as the risk of failure time was seen as very low.
	Integrity testing UF	An operation method that previously has caused failures of breakage with fibers, after the membrane was taken back into operation. However it is claimed that the procedure used today cannot cause any of these breakages after the racks are back in operation. Therefore this is not included in the calculation.
	Module failure (fiber physically breaks) UF	It happens all the time and it is known in what number it is expected to be. It was considered as a part of the normal operation. However still considered as a risk particularly if it is not tested as required or if something leads many breakages of fibers.
Chloriantion	Failure to provide enough chlorine for needed disinfection level	It was at first not consider in the fault tree as it partly is due to the raw water. However a failure at the end of the process train is a microbiological risk and can also be seen as the chlorination is not dosed enough.
	Chlorination -found in critical event database	There were 3 failure found during 5 years. These were not considered as they are already a part of the estimations.

Appendix X: Different estimations of Ultra filtration failures

Description of UF failure	Estimation 1 of number of failures per year	Estimation 2 of number of failures per year
SCADA failure UF	0.40	2
Monitoring turbidity UF	2	6
Rack programming	2	0.4
Air entrapment	6	0.2
Valve failures	1	1
Pressure shocks	1	-
Fouling	2	-
Backflushing failure	3	-
Chemical cleaning failure but OT included in the calculation.	4	-
Coarse particle failure NOT included in the calculation.	0.5	-

Appendix XI: Origin of input data for the fault tree

Area	**Description of failure**	**Origin of in data**
Ozone failure	**Ozone dosing**	Based on estimation as no failures were found, however it was agred that failure had happend and also will happend in the future
	Ozone genertor	Based on critical event database 2009-2010
	Chillerplant	Based on critical event database 2009-2010
	VOD	Based on critical event database 2009-2010
	Air compressor	Critical event database 2009-2010
	PSA	Critical event database 2009-2010
	Residual monitoring	Estimation, be aware of the definition. The same estimation has been used throughout the study regarding monitoring.
	Water flow meter after inlet	Not defined as it is such a low risk and will not cause any problem if it happens
Power failure	**Power Dip**	Critical event database 2009-2010
	Power Outage	Critical event database 2009-2010
UF- failure estiamtions person 1	**Scada failure UF**	Estimation based on expert opinion 1
	Monitoring turbidity UF	Estimation based on expert opinion 1
	Rack programmng	Estimation based on expert opinion 1
	Air entrapment	Estimation based on expert opinion 1
	Coarse partice	Estimated as an increased risk for 1 week every 2nd year. Not possible to model, as the time span only represent an increased risk and not a failure
	Pressure shocks	Estimation based on expert opinion 1
	Fouling	Estimation based on expert opinion 1
	Chemical cleaning failure	Estimated as an increased risk for 1 week every third month. Not possible to model, as the time span only represent an increased risk and not a failure
	Backflushing failure	Estimation based on expert opinion 1
	Valve failures	Estimation based on expert opinion 1
UF- failure estiamtions person 1	**Rack programming**	Critical event database 2006-2010
	Scada failur	Critical event database 2006-2010
	Air entraped	Estimation based on expert opinion 2
	Monitoring turbidity	Estimation based on expert opinion 2
	Valve failures	Estimation based on expert opinion 2
Chloriantion	**Chlorination-data values**	Not used in the calculation, however numbers are from critical event database 2006-2010
	High amonium in water	Critical event database 2006-2010
	Dosing, chlorine	Estimation
	Monitoring	Estimation, same as all monitoring

Appendix XII: Model calculations

The distributions were firstly described as a Gamma distribution and by CB it was model as showed in appendix XIII, the model was based on the following:

To model the failure rate, λ-Gamma distribution

Scale:1/ β β is time period of measured failure [month]
Shape: α α = number of failures +1

To model the repair rate, μ were described in two ways:

Method 1: μ
Estimated failure time as a 5% and 95% probability [month]
P5: 95P of estimated failure time
P95: 5P of estimated failure time
Method 2: μ
Scale:1/ β β is the total time of all failures [month]
Shape: α

Method 1 or 2 depended on what the input data of the failure were given as.

P_F was calculated with equation 3.1 as described in Appendix XIII as ”P-MC”.

Furthermore to add μ and λ to the next level in the fault tree were performed with the following equations:

$$\lambda = \sum_{i=1}^{n} \lambda_i$$

$$\mu = \frac{\left(\left(\prod_{i=1}^{n} \mu_{\mathrm{i}}\right)\left(\sum_{n=1}^{n} \lambda_{\mathrm{i}}\right)\right)}{\left(\prod_{i=1}^{n}(\lambda_{\mathrm{i}} + \mu_{\mathrm{i}}) - \left(\prod_{n=1}^{n}(\mu_i)\right)\right)}$$

Appendix XIII: Performed simulations

	DATA FROM THE DATABASE / EXPERT ESTIMATIONS						DATA TO FAULT TREE									
							Uptime				Downtime					Probablity of failure
		Time period [months]	Number of failures (during measured period)	Duration of failure mean value [min]	Duration of failure minutes [min]	Duration of failure maximum [min]	No. of events	α	β	λ	P05% [month] 1/μ	P95% [month] 1/μ	α	β	μ	P-MC
Ozone failures	Ozone dosing	216	5	300			5	6	216	**0.0277**			6	0.0347	**172.8**	**0.0001607**
	Ozone genertor	24	21		9.047619	60	21	22	24	**0.9166**	0.000209	0.001389			**2362.6**	**0.000387**
	Chillerplant	24	8		5.0	60	8	9	24	**0.375**	0.000012	0.001389			**3723.0**	**0.0001007'**
	VOD	120	1	10			1	2	120	**0.0166**			2	0.000231	**8640.0**	**0.000000192**
	Air compressor	24	28		6.4	60	28	29	24	**1.2083**	0.00014	0.001389			**3050.8**	**0.0003951**
	PSA	24	13		8.1875	60	13	14	24	**0.5833**	0.000189	0.001389			**2545.2**	**0.0002291**
	Residual monitoring	12	4		5.0	60	4	5	12	**0.4166**	0.000012	0.001389			**3723.0**	**0.0001119**
Power failure	Power Dip	24	95	52.8			95	96	24	**4.00**			96	0.116	**826.3**	**0.00481**
	Power Outage	24	14	98.9			14	15	24	**0.625**			15	0.0321	**467.5**	**0.001335**
UF- estamtation 1	Scada failure UF	60	10	50	40.0	60	10	11	60	**0.1833**	0.000925	0.001389			**892.3**	**0.000205**
	Monitoring turbidity UF	12	4		40	60	4	5	12	**0.4166**	0.000925	0.001389			**892.3**	**0.000466**
	Rack programmng	12	2		40	60	2	3	12	**0.25**	0.000925	0.001389			**892.3**	**0.0002800**
	Air enrapment	2	1		0.5	25	1	2	2	**1,0000**	0.000012	0.000578			**29415.7**	**0.0000339**
	Course particle (SMALL RISK and not included in study)	24	1	1440												
	Pressure shocks	12	1	50	40	60	1	2	12	**0.1666**	0.000925	0.001389			**892.3**	**0.000186**
	Fouling	12	2	50	40.0	60	2	3	12	**0.25**	0.000925	0.001389			**892.3**	**0.0002800**
	Chemical cleaning failure (SMALL RISK and not included in study)	3	1	1440												
	Backflushing failure	12	3	120			3	4	12	**0.3333**			4	0.0083	**480.000**	**0.000693**
	Valve failures (Estimation)	12	1	60			1	2	12	**0.1666**			2	0.00138	**1440.0**	**0.000115**
UF-estamtion 2	Rack programming (Data)	60	2	50	40	60	2	3	60	**0.05**	0.000925	0.001389			**892.3**	**0.000056**
	Scada failure (Data)	60	10	50	40	60	10	11	60	**0.1833**			11	0.0116	**950.4**	**0.000192**
	Air entraped (Estimation)	60	1	50	40	60	1	2	60	**0.03333**	0.000925	0.001389			**892.3**	**0.0000373**
	Monitoring turbidity	12	6		40	60	6	7	12	**0.58333**	0.000925	0.001389			**892.3**	**0.000653**
	Valve failures (Estimation)	12	1	60			1	2	12	**0.16666**			2	0.00140	**1440.0**	**0.0001157**
Chloriantion	Chlorination-based on data values	60	5		60	120	5	6	60	**0.1**	0.0013	0.00277			**526.9**	**0.000189725**
	High amonium in water	24	12		60	120	12	13	24	**0.5416**	0.0013	0.00277			**526.9**	**0.001026**
	Dosing. chlorine (Estimation)	12	3		60	120	3	4	12	**0.3333**	0.0013	0.00277			**526.9**	**0.000632138**
	Monitoring Chlorine (Estimation)	12	1		60	120	1	2	12	**0.1667**	0.0013	0.00277			**526.9**	**0.00031616**

Appendix XIV: Results of the FTA

Description of event	Parameter		Mean	P05	P50	P95	Failure hours / year (mean value)
Microbiological quality failure	Probability of failure	P_F	1,5E-02	1,3E-02	1,5E-02	1,8E-02	133
	Uptime (days)	$1/\lambda$	2.3	2.1	2.4	2.7	
	Downtime (hours)	$1/\mu$	0.9	0.7	0.9	1.0	
Main ozonation failure	Probability of failure	P_F	2,1E-03	1,1E-03	1,9E-03	3,8E-03	18.6
	Uptime (days)	$1/\lambda$	8.6	7.1	8.5	10.3	
	Downtime (hours)	$1/\mu$	0.4	0.2	0.4	0.8	
UF failure (Estimation 1)	Probability of failure	P_F	2,8E-03	1,6E-03	2,5E-03	4,6E-03	24.3
	Uptime (days)	$1/\lambda$	11.7	7.1	11.4	17.7	
	Downtime (hours)	$1/\mu$	0.8	0.4	0.7	1.3	
Chlorination failure	Probability of failure	P_F	2,1E-03	1,2E-03	2,0E-03	3,1E-03	18.1
	Uptime (days)	$1/\lambda$	30.5	20.1	29.4	44.9	
	Downtime (hours)	$1/\mu$	1.4	1.1	1.4	1.8	
Power failure	Probability of failure	P_F	6,3E-03	4,9E-03	6,2E-03	7,9E-03	55.1
	Uptime (days)	$1/\lambda$	6.6	5.6	6.5	7.7	
	Downtime (hours)	$1/\mu$	1.0	0.8	1.0	1.2	
Conventional treatment	Probability of failure	P_F	4,2E-03	1,4E-03	3,5E-03	9,3E-03	36.7
	Uptime (days)	$1/\lambda$	30.0	13.9	27.4	54.0	
	Downtime (hours)	$1/\mu$	2.5	1.3	2.3	4.3	

Details of result for ozonation tree							
Monitoring of residual ozone	Probability of failure	P_F	2,3E-04	3,1E-05	1,2E-04	6,7E-04	2.04
	Uptime (days)	$1/\lambda$	94.0	40.3	76.1	206,3	
	Downtime (hours)	$1/\mu$	1,7E-02	3,5E-03	9,3E-03	4,9E-02	
Ozone production	Probability of failure	P_F	7,6E-04	2,7E-04	6,0E-04	1,7E-03	6.62
	Uptime (days)	$1/\lambda$	23.7	17.6	23,4	31.0	
	Downtime (hours)	$1/\mu$	0.2	0.2	0.3	0.9	
Oxygen production	Probability of failure	P_F	9,7E-04	3,5E-04	7,8E-04	2,2E-03	8.54
	Uptime (days)	$1/\lambda$	17.2	13.2	16.9	22.1	
	Downtime (hours)	$1/\mu$	0.4	0.2	0.3	0.9	
Ozone dosing	Probability of failure	P_F	1,9E-04	6,0E-05	1,5E-04	4,2E-04	1.63
	Uptime (days)	$1/\lambda$	1260.7	609.9	1136.9	2498.1	
	Downtime (hours)	$1/\mu$	5.0	2.4	4.4	9.7	
Values not used in overall microbiological failure							
UF failure (Estimation 2)	Probability of failure	P_F	1,20E-03	6,83E-04	1,11E-03	1,91E-03	10.5
	Uptime (days)	$1/\lambda$	31.4	20.1	30.3	46.2	
	Downtime (hours)	$1/\mu$	0.8	0.6	0.8	1.2	

Appendix XV: Hours of failure per year

Hours of failure per year (Mean value)					
	Trial 1 (10 000)	**Trial 2 (10 000)**	**Trial 3 (10 000)**	**Trial 4 (10 000)**	**Trial 5 (100 000)**
Microbiological quality failure	133.48	133.45	134.26	134.00	134.10
Main ozonation failure	18.62	18.61	18.59	18.45	18.63
UF failure (Estiamtion 1)	24.36	24.46	25.23	25.10	25.03
Chlorination failure	18.13	17.98	18.07	18.09	18.04
Power failure	55.07	55.11	55.09	55.07	55.11
Conventional treatment	36.73	36.73	36.74	36.73	36.73
UF failure (Estiamtion 2)	10.52	10.52	10.52	10.52	10.53

Appendix XVI: Sensitivity analysis of Microbiological quality failure: P_F, 1/λ and 1/μ

Sensitivity: P- Microbiological quality failure	Rank Correlation
λ Power Dip	0.286
μ Power Dip	-0.283
μ Backflushing failure	-0.273
μ Air compressor	-0.248
λ Backflushing failure	0.247
μ Power Outage	-0.241
λ Power Outage	0.227
μ Ozone genertor	-0.194
λ Dosing. chlorine (estiamtion)	0.184
λ High amonium in water	0.179
μ High amonium in water	-0.124
μ PSA	-0.119
λ Monitoring (Chlorine)	0.118
λ Monitoring turbidity UF	0.112
μ Air enrapment	-0.110
μ Residual monitoring	-0.106
λ Fouling	0.100
λ Valve failures (esiamtion)	0.096
μ Dosing. chlorine (estiamtion)	-0.090
λ Rack programmng	0.085
μ Chillerplant	-0.084
μ Valve failures (esiamtion)	-0.081
λ Ozone genertor	0.060
μ Ozone dosing	-0.059
λ Pressure shocks	0.059

Sensitivity: 1/μ- Microbiological quality failure	Rank Correlation
λ Air enrapment	-0.424
μ Power Dip	-0.311
μ Backflushing failure	-0.284
μ Air compressor	-0.262
μ Power Outage	-0.256
μ Ozone genertor	-0.200
λ Backflushing failure	0.137
μ PSA	-0.135
μ High amonium in water	-0.133
λ Power Outage	0.117
μ Air enrapment	-0.109

μ Residual monitoring	-0.109
λ Air compressor	-0.108
μ Chillerplant	-0.106
μ Valve failures (esiamtion)	-0.097
λ High amonium in water	0.087
μ Dosing. chlorine (estiamtion)	-0.086
λ Dosing. chlorine (estiamtion)	0.082
λ Residual monitoring	-0.080
λ Ozone genertor	-0.078
λ PSA	-0.063
μ Ozone dosing	-0.055
λ Monitoring (Chlorine)	0.053
λ Chillerplant	-0.051
λ Ozone dosing	0.041

Sensitivity analysis: 1/λ- Microbiological quality failure	**Rank Correlation**
λ Air enrapment	-0.610
λ Power Dip	-0.390
λ Air compressor	-0.210
λ Residual monitoring	-0.190
λ Ozone genertor	-0.180
λ Monitoring turbidity UF	-0.170
λ Power Outage	-0.160
λ Fouling	-0.160
λ Backflushing failure	-0.160
λ High amonium in water	-0.150
λ PSA	-0.140
λ Dosing. chlorine (estiamtion)	-0.140
λ Rack programmng	-0.130
λ Chillerplant	-0.110
λ Pressure shocks	-0.110
λ Valve failures (esiamtion)	-0.100
λ Monitoring (Chlorine)	-0.100
λ Scada failure UF	-0.050
λ VOD	-0.030

Appendix XVII: Raw water input data for the QMRA model

NR = Normal risk level

ER = Enhanced risk level

	NOROVIRUS [genes/l]		**GIARDIA** [cysts/l]		**CRYPTOSPORIDIUM** [oocysts/l]	
	NR	ER	NR	ER	NR	ER
P05	0	0.003	0	701	0	972
P50	0.002	0.504	0.250	7334	0	2510
P95	0.340	85.0	2.00	86,300	3.0	26,000
Mean	0.286	71.5	0.506	24,200	0.55	7,120
Scale α	0.430	108.15	1.01	54,101	2.54	17,322
Shape β	0.141	0.141	0.527	0.371	0.242	0.323

Appendix XVIII: Process input data for the QMRA model

Normal operation is showed with bold text and sub-optimal operation within brackets.

	Norovirus	*Giardia*	*Cryptosporidium*
Conventional treatment [Log removal][a] Number of lines: 2 (Coagulation and DAF has 2 lines each and rapid gravity sand filtration has 5 lines)			
Min	**1.2** (0.23)	**1.7** (0.71)	**1.7** (0.71)
Mean	**2.2** (1.2)	**2.6** (1.6)	**2.6** (1.6)
Max	**3.8** (2.8)	**3.5** (2.5)	**3.5** (2.5)
Main ozonation [Log inactivation] Number of lines: 1			
Min	**8.0**[b] (0)	**8.0**[b] (0)	**0.31**[a] (0)
Mean	**9.5**[b] (2.5)	**9.5**[b] (2.5)	**1.2**[a] (0.50)
Max	**10**[b] (4.0)	**10**[b] (4.0)	**2.0**[a] (0.70)
Granular activated carbon [Log removal][c] Number of lines: 5 (In reality there are 7 lines. but not all are in operation continuously)			
Min	**0.2** (0.1)	**0.4** (0.2)	**0.7** (0.3)
Mean	**0.4** (0.2)	**1.7** (0.8)	**0.9** (0.4)
Max	**0.7** (0.6)	**3.3** (1.5)	**1.1** (0.9)
Ultrafiltration [Log removal][c] Number of lines: 4 (In reality there are 6 lines. but not all are in operation continuously)			
Min	**6.0** (4.5)	**6.5** (5.0)	**6.5** (5.0)
Mean	**6.5** (5.0)	**7.0** (5.5)	**7.0** (5.5)
Max	**7.0** (6.0)	**7.5** (6.5)	**7.5** (6.5)
Chlorination [Log inactivation][b] Number of lines: 1			
Min	**8.0** (0)	**0.30** (0)	**0**
Mean	**9.5** (2.5)	**0.62** (0.10)	**0**
Max	**10** (4.0)	**0.90** (0.20)	**0**

[a] ***This process data were found through calculations of indicator organisms.***
[b] ***This process data were found through a CT-value calculation.***
[c] ***This process data were found in literature (Smeets et al.. 2006)***

Appendix XIX: Ct-value calculation for the ozonation at NGWRP

The CT-values were calculated as the equation below (Rush et al. 2002).

$$CT_{achieved} = \text{Conc. residual ozone} \times \frac{\text{minimum volume of water in the reservoir } (m^3)}{\text{maximum hourly flow rate } (m^3/min)}$$

CT-value calculated with outlet residual ozone concentration

(Assuming there are two sectors of the ozonation reactor tank)

Sector 1

(This sector is from the inlet to point B, where the second ozone dosing point is)

This sector is assumed to represent	**22%**	
of the total ozonation tank. This is based on measurement on the skis of the ozonation tank.		
Volume of ozonation tank (About 29*2*7.4)	**429.2**	m^3
Approximate value		
Minimum volume of water in the tank (V)	**320**	m^3
It was estimated that the ozonation tank is filled with 70% which corresponds to 300 m^3. Another estimation was that the water height is about 1.6 m, that corresponds to a volume of 343 m3. Therefore. an approximate mean value of these two estimations was used: 320 m^3. Concluded in discussion with expert Mueller, S. at WINGOC.		
Peak hourly flow (Q)	**1000**	m3/hour
Estimated by experts at the plant =	**16.7**	m3/min
Minimum volume of water in sector 1 (V)	**70.4**	m3
*Equals 0.22*320m^3*		
Ozone Contact A (Just before dosing point B)	**1.38**	mg/l
- residual ozone (mean value throughout april 2011)		
TDT = V/Q = *320 m^3/16.7m^3/min*	**4.2**	min
Baffling factor (BF) = Hydraulic factor = Fsc	**0.7**	(Superior)
In (Rush et al. 2002). the table can be seen for baffling factors.		
The baffling factor was estimated in coherence with expert Mueller, S. at WINGOC.		

Disinfectant contact time (TDT * BF)		**3.0**	min
CT(calculated sector 1) =		**4.1**	mg min/l
*Ozone contact A * Disinfectant contact time*			
Sector 2			
(This sector is from point B, where the second			
ozone dosing point is, to the outlet)			
This sector is assumed to represent		**78%**	
of the total ozonation tank.			
Peak hourly flow (Q)		**1000**	m^3/hour
	=	**16.7**	m^3/min
Minimum volume of water in sector 1 (V)		**249.6**	m^3
Ozone Contact C (Outlet) *- residual ozone (mean april 2011)*		**1.0**	mg/l
TDT = V/Q		**15.0**	min
Baffling factor (BF) = Hydraulic factor = Fsc		**0.7**	(Superior)
Disinfectant contact time (TDT * BF)		**10.5**	min
CT(calculated sector 2)		**10.48**	mg min/l
CT(total for sector 1 + 2) = 4.1 + 10.48 =		**14.6**	mg min/l
CT(calculated sector 1) + CT(calculated sector 2)			
This corresponds to:			
Norovirus log inactivation:		**> 10**	
Giardia log inactivation:		**> 10**	
Cryptosporidium log inactivation:		**1.2**	
According to Ødegaard (2009) and Smeets et al (2006).			

Below, another approach is described that could have been applied (but was not) to decide the log inactivations for the ozonation process.

Alternative approach when deciding log inactivations for the ozonation process:

A Ct value of 20 is said to be maintained at NGWRP with the dosing filosophy applied.

The ozonation tank was designed so that the retention time will at least be 20 min.

Ozone injection has to be sufficient to ensure that a residual of 1 mg/l is available before the 2nd and 3rd injection points. This dosing philosophy will ensure that the minimum CT requirement of 20 is adhered at all times.

CT-value	**20**	mg min/l
This corresponds to:		
Norovirus log inactivation:	**> 10**	
Giardia log inactivation:	**> 10**	
Cryptosporidium log inactivation:	**1.6**	

According to Ødegaard (2009) and Smeets et al (2006).

Appendix XX: Ct-value calculation for the chlorination at NGWRP

The CT-values were calculated as the equation below (Rush et al. 2002)

$$CT_{achieved} = \text{Conc. of } Cl_2 \times F_{SC} \times \frac{\text{minimum volume of water in the reservoir } (m^3)}{\text{maximum hourly flow rate } (m^3/min)}$$

CT-value with the present chlorine tank

A new reservoir is being built (where chlorine will be added as well). The water will first come to the "new reservoir" and then to the "old" one. In this study, only the "old" reservoir is taken into consideration.

Final residual of free chlorine (mean value at the outlet from the tank 2009-2010):	**1.2**	mg/l
Final residual of free chlorine (5% - percentile value at outlet from the tank 2009-2010)	**0.9**	mg/l
Hydraulic factor ($t_{10}/T = BF = F_{SC}$) of the chlorination tank:	**0.7**	
Superior because the tank is serpentine formed. Concluded in discussion with expert Mueller. S at WINGOC 2011.		
Volume of chlorine contact tank:	**1000**	m^3
Minimum volume of water in the tank:	**700**	m^3
Estimated value, concluded in discussion with expert Mueller, S. at WINGOC 2011.		
Maximum hourly flow rate:	**1000**	m^3/h
	= **17**	m^3/min
Estimated value, concluded in discussion with expert Mueller, S. at WINGOC 2011.		
Minimum retention time = 700 m^3/1000 m^3/h =	**42**	min
$CT_{achieved}$ = Final residual of free chlorine * F_{SC} * (minimum volume/maximum flow)		
$CT_{achieved}$ = 0.9 mg/l * 0.7 * (700 m^3/17 m^3/min) =	**26.5**	mg min/l
This corresponds to:		

Norovirus log inactivation:	**13.3**	
Giardia log inactivation:	**0.62**	
Cryptosporidium log inactivation:	**0**	
According to Ødegaard (2009) and Smeets et al (2006).		

Below, another approach is described that could have been applied (but was not) to decide the log inactivations for the chlorination process:

Alternative approach when deciding log inactivations for the chlorination process		
With this approach the QMRA program calculates a CT-value for the process.		
In data in the "free chlorine" process in the QMRA model:		
Initial residual free chlorine:	**2.1**	mg/l
The chlorine demand at this point of the treatment train is 0.9 mg/l according to an investigation performed by the City of Windhoek. The final residual free chlorine in the effluent of the chlorine tank is 1.2 mg/l, which is a mean value for the measured values 2009 – 2010.		
Travel time to consumer:	**60**	minutes
The time it takes for the water to reach the New Western Pump Station.		
Timestep	**1**	
Determines the level of detail in the calculation.		
pH	**8.5**	
Mean pH of measured values 2009-2010: 7.8, but 8.5 was the nearest value That could be used in the QMRA program tool.		
Temperature	**10-15**	°C
Mean water temperature of final water 2009-2010: 22°C, but 10-15°C was the nearest value that could be used in the QMRA program tool.		
Disinfectant decay rate:	**"Estimate from literature"**	
Result:		
Norovirus log inactivation:	**4.0**	
Giardia log inactivation:	**0.3**	
Cryptosporidium log inactivation:	**0**	
CT-value:	**16.1**	**mg min/l**

Appendix XXI: Daily and annual probability of infection

The annual probability of infection (P_I) was calculated with equation 3.4. As $t_{(event)}$, the result from the FTA were applied, which are showed in the table below. These were calculated as probability of failure for a specific process (P50) multiplied with 365 days. $t_{(normal)}$ was achieved by subtracting $t_{(event)}$ from 365 days.

Conventional treatment, $t_{(event)}$	1.53	days/year
Main ozonation failure, $t_{(event)}$	0.78	days/year
UF failure, $t_{(event)}$	1.02	days/year
Chlorination failure, $t_{(event)}$	0.76	days/year
Power failure, $t_{(event)}$	2.29	days/year

$P_{inf(normal)}$ and $P_{inf(event)}$ were obtained from the QMRA-modelling and these values are presented below, together with the calculated P_I.

Scenario 1 - Normal operation

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(normal)}$	0	0	0
Daily probability of infection (P50), $P_{inf(normal)}$	0	0	6.88E-15
Daily probability of infection (P95), $P_{inf(normal)}$	0	0	6.63E-08
Annual probability of infection (P05), P_I	**0**	**0**	**0**
Annual probability of infection (P50), P_I	**0**	**0**	**2.51E-12**
Annual probability of infection (P95), P_I	**0**	**0**	**2.42E-05**

Scenario 2 - Epidemic 40 days (increased raw water levels)

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	6.15E-14
Daily probability of infection (P50), $P_{inf(event)}$	0	0	7.27E-11
Daily probability of infection (P95), $P_{inf(event)}$	0	4.44E-13	7.15E-04
Annual probability of infection (P05), P_I	**0**	**0**	**2.46E-12**
Annual probability of infection (P50), P_I	**0**	**0**	**2.91E-09**
Annual probability of infection (P95), P_I	**0**	**1.77E-11**	**2.82E-02**

Scenario 3 - Sub-optimal operation in the conventional treatment process

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	0
Daily probability of infection (P50), $P_{inf(event)}$	0	0	6.23E-14
Daily probability of infection (P95), $P_{inf(event)}$	0	1.11E-16	6.04E-07
Annual probability of infection (P05), P_I	**0**	**0**	**0**
Annual probability of infection (P50), P_I	**0**	**0**	**2.58E-12**
Annual probability of infection (P95), P_I	**0**	**0**	**2.49E-05**

Scenario 4 - Sub-optimal operation in the ozonation process

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	0
Daily probability of infection (P50), $P_{inf(event)}$	0	0	4.82E-14
Daily probability of infection (P95), $P_{inf(event)}$	0	1.17E-10	4.69E-07
Annual probability of infection (P05), P_I	**0**	**0**	**0**
Annual probability of infection (P50), P_I	**0**	**0**	**2.54E-12**
Annual probability of infection (P95), P_I	**0**	**8.01E-11**	**2.45E-05**

Scenario 5 - Sub-optimal operation in the UF process

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	1.11E-16
Daily probability of infection (P50), $P_{inf(event)}$	0	0	2.15E-13
Daily probability of infection (P95), $P_{inf(event)}$	0	0	6.63E-08
Annual probability of infection (P05), P_I	**0**	**0**	**0**
Annual probability of infection (P50), P_I	**0**	**0**	**2.70E-12**
Annual probability of infection (P95), P_I	**0**	**0**	**2.42E-05**

Scenario 6 - Sub-optimal operation in the chlorination process

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	0
Daily probability of infection (P50), $P_{inf(event)}$	0	0	6.88E-15
Daily probability of infection (P95), $P_{inf(event)}$	0	0	6.63E-08
Annual probability of infection (P05), P_I	**0**	**0**	**0**
Annual probability of infection (P50), P_I	**0**	**0**	**2.51E-12**
Annual probability of infection (P95), P_I	**0**	**0**	**2.42E-05**

Scenario 7 - Sub-optimal operation in the conventional treatment and the following processes are affected

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	1.33E-15
Daily probability of infection (P50), $P_{inf(event)}$	0	3.33E-16	1.39E-12
Daily probability of infection (P95), $P_{inf(event)}$	1.11E-16	1.06E-09	4.20E-06
Annual probability of infection (P05), P_I	**0**	**0**	**0**
Annual probability of infection (P50), P_I	**0**	**0**	**4.30E-12**
Annual probability of infection (P95), P_I	**0**	**1.37E-09**	**2.95E-05**

Scenario 8 - Realistic (sub-optimal operation for all processes included)

	Norovirus	*Giardia*	*Cryptosporidium*
Annual probability of infection (P05), P_I	**0**	**0**	**2.96E-14**
Annual probability of infection (P50), P_I	**2.30E-14**	**1.94E-14**	**3.43E-11**
Annual probability of infection (P95), P_I	**3.17E-09**	**7.54E-09**	**3.46E-05**

Scenario 9 - Adding UV light process

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	0
Daily probability of infection (P50), $P_{inf(event)}$	0	0	0
Daily probability of infection (P95), $P_{inf(event)}$	0	0	6.54E-11
Annual probability of infection (P05), P_I	**0**	**0**	**0**
Annual probability of infection (P50), P_I	**0**	**0**	**0**
Annual probability of infection (P95), P_I	**0**	**0**	**2.39E-08**

To illustrate power failure. daily probabilities of infection ($P_{inf(event)}$) were obtained for the case when all the processes are set into sub-optimal operation (see table below).

Sub-optimal operation for all processes (to illustrate power failure)

	Norovirus	*Giardia*	*Cryptosporidium*
Daily probability of infection (P05), $P_{inf(event)}$	0	0	1.30E-14
Daily probability of infection (P50), $P_{inf(event)}$	1.01E-14	8.55E-15	1.39E-11
Daily probability of infection (P95), $P_{inf(event)}$	1.40E-09	3.29E-09	4.20E-06

Example of the calculation of P_I

The annual probability of infection by *Cryptosporidium* for the 95th percentile of scenario 9 was calculated as follows:

$$P_{ani} = 1-((1-P_{inf(normal)})^{t(normal)} * (1-P_{inf(sub\text{-}optimal\ conv.\ treatm.)})^{t(failure\ conv.\ treatm.)} * (1-P_{inf(sub\text{-}optimal\ ozonation)})^{t(failure\ ozonation)} * (1-P_{inf(sub\text{-}optimal\ UF)})^{t(failure\ UF)} * (1-P_{inf(sub\text{-}optimal\ chlorination)})^{t(failure\ chlorination)} * (1-P_{inf(power\ outage)})^{t(failure\ power)})) =$$

$$= 1-((1-6.63*10^{-8})^{365-(1.29+0.68+0.91+0.73+2.27)} * (1-6.04*10^{-7})^{1.29} * (1-4.69*10^{-7})^{0.68} * (1-6.63*10^{-8})^{0.91} * (1-6.6310^{-8})^{0.73} * (1-4.20*10^{-6})^{2.27} =$$

$$= 2.39*10^{-8}$$